A LABORATORY STUDY ON STRENGTH AND SWELLING BEHAVIOR OF CLAYS WITH HIGH SWELLING POTENTIAL STABILIZED BY DEEP AND SHALLOW MIXING METHODS USING TRAVERTINE

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“Bu tezdeki tüm bilgilerin akademik kurallara ve etik ilkelere uygun olarak elde edildiğini ve sunulduğunu; ayrıca bu kuralların ve ilkelerin gerektirdiği şekilde, bu çalışmadan kaynaklanmayan bütün atıfları yaptığımı beyan ederim.”

Almukhtar Hasan Salih IQBAS

ABSTRACT

Master Thesis

A LABORATORY STUDY ON STRENGTH AND SWELLING BEHAVIOR OF CLAYS WITH HIGH SWELLING POTENTIAL STABILIZED BY DEEP AND SHALLOW MIXING METHODS USING TRAVERTINE

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There is a wide application area in the construction industry regarding the stabilization of clay soils. It is widely preferred to use various additives to increase the engineering properties of such soils, and with this method, the soils are made more suitable for construction purposes. These additives are used to reduce the sensitivity of clay soils to volume change, increase their bearing capacity and improve their general mechanical properties. This study examines the usability of geopolymer activated by adding various amounts of travertine and potassium hydroxide (KOH) in the improvement of clayey soils and its potential for use in two basic mixing techniques: deep mixing and shallow mixing. It has become clear that adding KOH-activated travertine additive at various rates to the bentonite-marl mixture, which has a high swelling potential, significantly reduces the swelling capacity of the soil. In the study, it was determined that the optimal ratio was 15%

travertine additive activated with 1 M KOH. In general, adding travertine has been found to help reduce swelling, but adds even more when the activator KOH is added. In addition, it has been evaluated that the application of this material by shallow and deep mixing methods can give effective results on the ground. An important understanding of soil stabilizing strategies was gained from the comparison of shallow and deep mixing procedures. The study aimed to assess the effectiveness of shallow mixing in minimizing soil swelling by introducing a mid-layer adjustment with a varied amount of travertine in the bentonite-marl mixture. The findings show encouraging results, indicating that travertine stabilization combined with shallow mixing procedures can effectively improve soil stability and reduce the likelihood of swelling. This emphasizes how crucial it is to investigate cutting-edge stabilization techniques for environmentally friendly soil management techniques.

Key Word **:** Swelling Soils, Soil Stabilization, Travertine, KOH, Bentonite, Marl.

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ÖZET

Yüksek lisans Tezi

TRAVERTEN KULLANILARAK DERİN VE SIĞ KARIŞTIRMA YÖNTEMLERİYLE STABİLİZE EDİLEN YÜKSEK ŞİŞME POTANSİYELİNE SAHİP KİLLERİN DAYANIM VE ŞİŞME DAVRANIŞLARI ÜZERİNE BİR LABORATUVAR ÇALIŞMASI

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Killi zeminlerin stabilizasyonu konusunda inşaat endüstrisinde geniş bir uygulama alanı bulunmaktadır. Bu tür zeminlerin mühendislik özelliklerini artırmak için çeşitli katkı maddelerinin kullanılması yaygın bir şekilde tercih edilmekte olup bu yöntem ile zeminler inşaat amaçları için daha uygun hale getirilmektedir. Bu katkı maddeleri, kil zeminlerin hacim değişimine duyarlılığını azaltmak, taşıma kapasitelerini artırmak ve genel mekanik özelliklerini iyileştirmek amacıyla kullanılmaktadır. Bu çalışma çeşitli oranlarda traverten eklenerek ve potasyum hidroksit (KOH) ile aktive edilen geopolimerin killi zeminlerin iyileştirilmesinde kullanılabilirliği ve derin karıştırma ve sığ karıştırma olmak üzere iki temel karıştırma tekniği özelinde kullanım potansiyelini incelemektedir. Yüksek derecede şişme potansiyeline sahhip bentonit-marn karışımına KOH ile aktive edilen traverten katkısı çeşitli oranlarda ekledikten sonra zeminin şişme kapasitesini önemli ölçüde azalttığı açıkça ortaya çıkmıştır. Çalışmada optimal oranın, 1 M KOH ile aktive edilen %15 traverten katkısının olduğu belirlenmiştir. Genel olarak, traverten eklemenin şişmeyi azaltmaya yardımcı olduğu, ancak aktivatör KOH eklenildiğinde daha da fazla katkı sağladığı bulunmuştur. Ayrıca söz konusu bu malzeminin sığ ve derin karıştırma yöntemi ile uygulanmasının zeminde etkin bir sonuç verebileceği değerlendirilmiştir. Yüzeysel ve derin karıştırma prosedürlerinin karşılaştırılması yoluyla toprak stabilizasyon stratejilerine ilişkin önemli bir anlayış elde edilmiştir. Çalışma, bentonit-marn karışımında değişen miktarda traverten ile bir orta katman ayarlaması yaparak toprak şişmesini en aza indirmede sığ karışımın etkinliğini değerlendirmeyi amaçladı. Bulgular, sığ karıştırma prosedürleriyle birlikte traverten stabilizasyonunun toprak stabilitesini etkili bir şekilde iyileştirebileceğini ve şişme olasılığını azaltabileceğini gösteren cesaret verici sonuçlar ortaya koyuyor. Bu, çevre dostu toprak yönetimi teknikleri için en son stabilizasyon tekniklerini araştırmanın ne kadar önemli olduğunu vurgulamaktadır.

Anahtar Sözcükler : Şişen Zeminler, Zemin Stabilizasyonu, Traverten, KOH, Bentonit, Marn.
Bilim Kodu : 91105

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SİMGELER VE KISALTMALAR DİZİNİ

SİMGELER

$Cr_{eş}$: krom eşdeğerliliği
$Ni_{eş}$: nikel eşdeğerliliği
Ag : gümüş
Al : alüminyum
Ar : argon
Au : altın
Cu : bakır
H_2 : hidrojen
He : helyum
Mo : molibden
Ni : nikel
$\mathrm{erf}(z)$: hata işlevi
γ : birim hacim ağırlığı
$\Gamma(x)$: gama işlevi
θ : kutupsal açı
σ : normal gerilme
σ_C : tek eksenli basınç dayanımı

KISALTMALAR

ASTM : American Society for Testing and Materials
AWS : American Welding Society (Amerika Kaynak Topluluğu)
DIN : Deutch Industrie Normen (Alman Endüstri Normları)
EN : European Norm (Avrupa Normu)
IIW : International Institute of Welding (Uluslararası Kaynak Enstitüsü)
ITAB : Isı Tesiri Altında Kalan Bölge
TS : Türk Standardı

CHAPTER 1

INTRODUCTION

Clay minerals are a class of naturally occurring, fine-grained minerals that have played a significant role in the fields of geotechnical engineering, environmental science, and materials science due to their unique physical and chemical properties. Their ability to swell and shrink in response to changes in moisture content has been a subject of extensive research and investigation. Understanding and mitigating the swelling behavior of clays with high swelling potential is crucial, as it can have profound implications for infrastructure stability, environmental contamination, and various construction-related issues. The focus of this study is to explore the laboratory-based methods for stabilizing clay soils with high swelling potential using travertine and travertine activated with NOH, through deep and shallow mixing techniques [1].

Clay minerals, which include but are not limited to montmorillonite, kaolinite, illite, and smectite, have the remarkable capacity to adsorb and retain water, leading to swelling when exposed to moisture and shrinking when subjected to drying conditions. This swelling-shrinking behavior can result in significant challenges in civil engineering and construction projects. Infrastructure built on clayey soils, such as roads, embankments, foundations, and retaining structures, is susceptible to damage and deformation due to the volume changes associated with clay swelling. Moreover, these swelling and shrinking cycles can lead to cracks, instability, and even failure in the constructed structures. Hence, controlling and mitigating the swelling behavior of clay soils is of paramount importance [2].

Stabilization of clay soils is a widely accepted practice in the construction industry. It involves the introduction of various additives to enhance the engineering properties of the soil, making it more suitable for construction purposes. These additives are designed to reduce the susceptibility of clay soils to volume changes, increase their load-bearing capacity, and improve their overall mechanical properties. Stabilization is particularly valuable when dealing with clay soils exhibiting high swelling potential.

Travertine, a type of sedimentary rock, is another material that has shown promise in soil stabilization. With its unique composition and structure, travertine can be utilized to enhance the mechanical properties of clayey soils [3]. The use of travertine for stabilization purposes is relatively novel, and its potential benefits need to be explored further. This research seeks to evaluate the impact of travertine as a stabilizing agent for high-swelling clay soils in shallow and deep missing methods.

In addition to the choice of stabilizing agents, the methods used to mix these agents with the clay soils also play a crucial role in the effectiveness of stabilization. This study will investigate two primary mixing techniques: deep mixing and shallow mixing. Deep mixing involves the mechanical incorporation of stabilizers into the soil at greater depths, typically through specialized equipment like augers or blades. Shallow mixing, on the other hand, focuses on mixing the stabilizers with the surface layer of the clay soil. The choice of mixing method can influence the distribution and effectiveness of the stabilizing agent, and it is essential to compare these methods to identify the most suitable approach for clay soil stabilization [4].

The experimental phase of this study was meticulously designed to evaluate the strength and swelling behavior of high-swelling clay soils stabilized with travertine and travertine activated with NaOH. The clay samples were subjected to both deep and shallow mixing methods, and a series of laboratory tests were conducted to measure the changes in their physical and mechanical properties. Key parameters such as unconfined compressive strength (UCS), Atterberg limits, and swelling potential were carefully monitored before and after the stabilization process. These tests provided valuable data on the efficacy of the stabilization techniques and the improvements in the clay soils' behavior under varying moisture conditions [5].

In the deep mixing method, the stabilizing agents were incorporated into the clay at depths typically greater than one meter using specialized equipment designed for thorough mixing. This method aimed to create a homogenous mixture of clay and stabilizer at significant depths, which is expected to enhance the long-term stability and load-bearing capacity of the soil. The deep mixing process was carefully controlled to ensure consistent distribution of the stabilizers throughout the soil column, and the resulting samples were subjected to rigorous testing to evaluate their performance [6].

The shallow mixing method involved the incorporation of stabilizing agents into the top layer of the clay soil, typically up to a depth of 0.5 meters. This method is often preferred for its simplicity and cost-effectiveness, particularly in projects where deep stabilization is not feasible or necessary. The shallow mixing process was performed using hand tools and mechanical mixers to ensure uniform distribution of the stabilizers within the surface layer. The stabilized samples were then tested to determine the improvements in their mechanical properties and swelling behavior, providing a basis for comparison with the deep mixing method [7].

The results of the laboratory tests indicated significant improvements in the strength and swelling behavior of the clay soils stabilized with travertine and travertine activated with NaOH. Both deep and shallow mixing methods demonstrated their potential in reducing the swelling potential and enhancing the mechanical properties of the clay soils. However, the deep mixing method showed superior performance in terms of achieving higher strength and more uniform stabilization, while the shallow mixing method offered a practical and cost-effective solution for surface stabilization. These findings highlight the importance of selecting the appropriate stabilization technique based on the specific requirements of the construction project and the characteristics of the clay soil being stabilized [8].

The outcome of this research is expected to shed light on the potential of travertine as effective stabilizing agents for clay soils with high swelling potential. It will also provide insights into the advantages and disadvantages of deep and shallow mixing methods. Ultimately, the knowledge generated from this study will contribute to the development of sustainable and environmentally friendly practices in geotechnical engineering, offering practical solutions to the challenges posed by high-swelling clay soils in construction and civil infrastructure projects [4].

Bose [9] conducted an investigation into the effects of fly ash additives, by weight percentages of 0-20-40-60-90, on bentonite. The experimental results revealed significant alterations in plasticity characteristics, shrinkage limit, free swell index, and swelling pressures. Additionally, the particle size distribution was affected. The maximum dry unit weight values increased up to 20% fly ash addition and gradually decreased beyond this threshold. Moreover, the maximum unconfined compressive strength was observed at 20% fly ash addition, with higher proportions of fly ash resulting in decreased unconfined compressive strength.

Gadouri et al. [10] explored the effects of natural pozzolan, lime, gypsum, and various mixtures of these materials on two different types of clay. Their research, conducted with a maximum curing period of 120 days, revealed increased unconfined compressive values and plastic limits, along with reduced liquid limits for all samples. Interestingly, the incorporation of gypsum along with lime showed minimal variations in the experimental results.

Abiodun and Nalbantoglu [11] conducted laboratory studies involving lime column treatment on a soil containing 64% clay and a free swell index of 63.33. Their findings indicated a reduction in liquid limit and plastic limit values as the curing period increased, along with a decrease in the shrinkage limit. Furthermore, the optimum moisture content decreased, and unconfined compressive values increased as curing duration progressed.

Ali and Mohamed [12] emphasized the critical importance of the initial 12 hours in the interaction between clay-lime mixtures for the formation of cementitious compounds. They observed that experiments conducted at 40°C yielded a higher formation of cementitious compounds compared to those conducted at 20°C. It was noted that permeability coefficients increased with wetting time and environmental temperature. The unconfined compressive strength values decreased as the contact time between the samples extended.

López-Lara et al. [13] mixed a highly compressible clay with 6% lime, resulting in a significant reduction in liquid limit (from 72% to 49%) and plasticity index (from 40% to 13%). Swell tests at 1 kPa pressure revealed a 0.58% swelling for lime-treated samples and 10.58% for untreated samples.

Mohanty [14] mixed Class CH soil with fly ash at proportions of 15-20-30%. However, the experiments indicated that, despite increasing mix ratios, there was no significant change in liquid limit, plastic limit, maximum dry unit weight, optimum moisture content, or unconfined compressive strength of the soil.

Zhu et al. [15] conducted laboratory tests on lime-stabilized silty clay from Jilin Province, China. The study aimed to comprehensively analyze the geotechnical properties and microstructures of the soil by varying lime content and curing duration. Their research involved tests on compression properties, Atterberg limits, particle size distribution, pH, tensile behavior, peak strength, shear strength parameters, and California bearing ratio (CBR). The results highlighted the considerable influence of lime content and curing duration on the geotechnical properties and microstructure of the lime-stabilized silty clay. An increase in lime content led to enhancements in optimum moisture content, liquid limit, plastic limit, silt fraction, pH, and CBR, while plasticity index decreased. Furthermore, the addition of lime transformed the silty clay from a ductile material into a brittle one. An approximate lime content of 5-7% was determined as the optimum for silty clays in Jilin City. Scanning electron microscopy (SEM) images revealed the formation of a white cementitious gel after lime addition, with peaks related to smectite, illite, kaolinite, and quartz appearing sharper after lime stabilization and a 90-day curing period. These findings underscore the significant impact of lime on the geotechnical properties of lime-stabilized silty clay, which is intricately linked to its microstructural organization.

Di Sante et al. [16] conducted a laboratory test program on soft clays in Finland, both with and without 7% quicklime treatment, to examine the effects of water content and curing duration. Their research, supported by microstructural analysis, revealed that the addition of lime over a wide range of water content (10-40%) resulted in increased hydraulic conductivity, primarily due to reduced compressibility and increased shear strength in the soil. However, for highly wetted clay samples (90-130% water content), lime addition showed less improvement in mechanical properties, indicating the need for a drying process if lime is to be used for the reutilization of typically high-water content, sensitive clays.

In Tekin study [17], geopolymer composite pastes (GCM) were produced using wastes of marble, travertine and natural pozzolan, with 1 M, 5 M and 10 M NaOH as alkali-activator. Curing process were done at 20, 45 and 75 °C temperatures for 24 h in an oven. And after that GCMs were exposed to wet and dry condition separately. The strength tests were done on the 2nd, 3rd, 7th, 28th and 90th days of curing period. The compressive strengths of the specimens in the wet conditions were reduced depending on time, but in dry conditions were increased with curing time.

Keskin et al. [1] study determine the effect of travertine powder on the swelling, strength, and permeability properties of weak and swellable soils. Within the scope of the study, soil improvement performance of travertine powder, which can be used as a soil improvement tool, was analyzed in detail, and the effect of travertine powder on the hydraulic and strength properties of the soil was discussed comparatively. Waste powder from travertine quarries taken from Eskipazar (Turkey) and Bentonite clay with high swelling potential taken from Tokat (Turkey) was used in the study. While the permeability coefficient, unconfined compressive strength, cohesion, and internal friction angle of bentonite samples with the additive increased over the curing time, the swelling pressure value decreased.

CHAPTER 2

SWELLING SOILS

To consider the presence of expansive soils, a soil must contain a significant amount of clay minerals and likely belong to the CL or CH groups in the Unified Soil Classification System (USGS). However, it should be noted that soils in the ML, MH, and SC groups may also exhibit swelling characteristics. Expansive soils typically manifest distinctive shrinkage cracks and other evidence of prior swelling upon drying. Such visual identification serves as an initial step, but further detailed information should be obtained before developing specific design recommendations [18].

Disintegrated shales and basalts, highly consolidated clays, Tertiary and Quaternary alluvial sediments, and geological units related to the formation of expansive soils are described as geological units. Expansive soils are formed through the weathering of various rock types such as sandstone, limestone, metamorphic, and volcanic rocks, which contain abundant silicate minerals that can easily transform into clay minerals like montmorillonite and illite through processes involving oxidation, hydration, dehydration, and ion exchange [19].

The variety of clay minerals arises from changes in the parent rock's weathering stage, and this diversity during the weathering phase directly impacts the soil's swelling characteristic [20]. When assessing the structural formation of clay minerals, it is important to note that structural groupings tend to be more harmonious as these groups exhibit similar engineering properties, even though both montmorillonite and kaolinite minerals originate from the weathering of igneous rocks. However, due to differences in weathering conditions, montmorillonite minerals exhibit significantly higher swelling potential compared to kaolinite minerals.

Clay minerals, which are highly active in an electrochemical sense, significantly affect the engineering properties of soils due to their very small particle sizes and depend on the content within the soil mass. Chen [20] emphasized the importance of identifying mineral varieties in evaluating swelling potential, as swelling behavior is directly related to the mineralogical characteristics of clay minerals.

Swelling potential is a term used to express the swelling property of a soil. There is no consensus regarding the definition and determination of swelling potential. Swelling potential is typically considered a term encompassing the soil's percentage of swelling and swelling pressure [21]. The percentage of swelling represents the percentage change in volume of a soil sample prepared in an unaltered or specified initial condition when it reaches saturation, relative to its initial volume. It can be determined through vertical strain or lateral diameter changes resulting from keeping the soil sample underwater under one-dimensional oedometer conditions (conditions where lateral deformations are constrained) [10].

Another essential term that characterizes the swelling behavior of soils is swelling pressure. Swelling pressure is the pressure required to maintain the soil-water system at the desired void ratio when clay absorbs water or electrolyte. Various methods have been developed by researchers to measure swelling pressure. These methods can generally be categorized into two groups: constant load oedometer tests and constant volume oedometer tests [18]. Swelling pressures and swelling amounts are significantly influenced by the methods used. Sridharan et al. [22] investigated the factors affecting swelling pressures in a soil known as black cotton (montmorillonite). They determined swelling pressures using the free swell oedometer test, the loaded swell test, and the constant volume test. According to the data obtained from these tests, the free swell oedometer test yielded the highest swelling pressure, the loaded swell test produced the lowest value, and the constant volume test provided an intermediate value between the two methods.

2.1. MECHANISM of SWELLING

The phenomenon of clay swelling is the result of the balance of interaction forces between clay surfaces, ions, and the liquid present in the environment. Clay particles are platelets with positive charges at their edges and negative charges on their surfaces. The negative charges on the surfaces create an equilibrium with the electric forces and cations in the absorbed water on the plate surface. Changes in the liquid quantity or the chemical nature of the liquid alter the clay-liquid interaction. Consequently, the internal electrochemical forces within the system change. This results in a change in the soil volume until equilibrium is reestablished between capillary tension in the soil water and externally applied forces [23].

In swelling, the crystal chemistry of clay minerals plays a significant role. For instance, montmorillonite, which has a high swelling potential, is very similar to illite mineral in terms of crystal structure. However, illite mineral has a higher electron charge per unit surface area compared to montmorillonite. As a result, the interlayer bonds in illite minerals are much stronger due to differences in weathering conditions, and thus, illite minerals cannot disrupt these strong bonds and intercalate between layers [24].

The movement of water within the soil depends on the energy of the water in the soil relative to the energy of free water. When the energy of water in the soil is lower than that of free water, water tends to move towards the soil. In clayey soils, water typically causes volume expansion, while in coarse-grained soils, it fills voids without causing volume change. The presence of swelling clay minerals in fine-grained soils with high consolidation rates or low moisture content leads to swelling due to reduced internal stresses related to the hydration of cations on clay particle surfaces [25].

Swelling in clay soils is primarily controlled by two fundamental mechanisms. The first mechanism involves swelling between clay particles, which is a common feature in all clay soils. In dry conditions, the capillary voids between the crystals hold the clay crystals together through surface tension forces. These surface tension forces decrease with increased water content, leading to swelling in clay soils. The second mechanism, known as intra-crystalline swelling, is typically observed in montmorillonite clay minerals. In this mechanism, when clay comes into contact with water, water enters between the weakly bonded layers of the crystal, leading to swelling in the clay [26].

The mineralogical composition and structure of clay minerals determine their physical properties. When there is a charge imbalance in the TOT structure with an absolute value less than approximately 0.9 and greater than 0.2 for each unit cell, interlayer cations are less fixed, and they can be exchanged with another ion. Other polar or ionic molecules can be added to the interlayer structure. Changes in crystal structure may occur when Fe^{+3} or Mg^{+2} ions replace Al^{+3} ions in the octahedral structure or when Al^{+3} ions replace Si^{+4} ions in the tetrahedral structure. To restore the disrupted charge balance, ions like Na^{+} and Ca^{+2} are adsorbed. These ions are referred to as exchangeable cations and are naturally present in the interlayer water. Na^{+} ions, in particular, cause a significant amount of water to be drawn into the layers, leading to greater swelling of the clay mineral compared to Ca^{+2} ions [27].

2.2. FACTORS AFFECTING SWELLING

Ramana [28] have categorized the factors influencing soil swelling behavior into three main groups. These groups are summarized in Tables 2.1, 2.2, and 2.3 in tabular form.

Table 0.1. Soil Properties Affecting Swelling Potential [28]

Factor	Definition
Clay Mineralogy	Minerals that cause changes in soil volume are generally montmorillonites, vermiculites, and similar minerals. Illites and kaolinites can swell, especially when the particle size is very small.
Soil water chemistry	Increased cation concentration and cation valency inhibit swelling. For example, Mg2+ cations in soil water cause less swelling compared to Na+ cations.

Soil Structure and Fabric	Flocculated clays exhibit a greater tendency to swell compared to dispersed clays. Cementation reduces swelling. The fabric and structure change as a result of compression or kneading at high water contents. Kneading compression has been shown to create discrete structures with lower swelling potential than static compression at low water contents.
Soil Suction	Soil suction is an independent effective stress variable expressed with negative pore water pressure in unsaturated soils. Saturation depends on gravity, void size and shape, surface tension, the electrical and chemical characteristics of soil particles, and the nature of water.
Plasticity	Generally, soils with plastic behavior over a wide range of moisture content and a high liquid limit have a higher swelling and shrinkage potential.
Dry Unit Weight	High unit weights indicate that particles are closer to each other, which means larger interparticle forces and a higher swelling potential.

Table 0.2. Environmental Factors Affecting Swelling Potential [28]

Factor	Definition
Initial Moisture Condition	The tendency or capacity of a dry swellable soil to imbibe or absorb water is greater than that of the same soil at high moisture contents.
Moisture Changes	Moisture changes are primarily influenced by climate, groundwater levels, drainage, artificial water sources, vegetation, permeability, and temperature.

Table 0.3. Effect of Stress Conditions on Swelling Potential [28]

Factor	Definition
Stress History	Overconsolidation ratio, repeated wetting-drying, and aging have significant effects on swelling.
Site Conditions and Soil Profile	The initial stress state in a soil, the location and thickness of layers with swelling potential, and the soil's swelling have significant effects.
Loading	Overload attempts to balance interparticle forces and reduce swelling.

2.3. CLAY MINERALOGY

In soil classification systems, clay particles are defined as particles with a diameter of 0.002 mm or smaller, often referred to as colloidal-sized particles. However, particle size alone cannot provide sufficient information to determine the behavior of clay particles. In fine-grained soils, one of the most critical factors in addition to particle size is their mineralogical composition [20].

Clays are primarily formed through the weathering of volcanic or sedimentary rocks. Electrical forces acting on the surfaces of clay minerals or colloidal-sized particles are generally greater than gravitational forces. Clay-containing soils, in general, undergo volume changes to varying degrees due to changes in water content. This volume change manifests as shrinkage when the water content decreases and swelling when it increases. Significant volume changes in swelling soils are typically observed in climates with alternating dry and rainy seasons [22]. Clay content and mineralogical composition are the key factors controlling the swelling characteristics of swelling soils.

2.3.1. Formation of Clay Minerals

In the formation of clay minerals, the chemical composition of the parent rock, the degree of weathering resulting from physical and chemical interactions, and the determination of the clay mineral are of primary importance [29]. The transformation of minerals that constitute rocks into clay minerals involves two main processes: physical and chemical processes. The physical process results in the mechanical breakdown and fragmentation of the source rock. In this process, fractures, cracks, and the intrusion of water and active solutions into the source rock are facilitated by the fractures and openings, while fragmentation increases the specific surface area, accelerating chemical reactions. The chemical process includes processes such as carbonation and hydroxylation (interaction between acids and bases), oxidation, and reactions (electron exchange) [30].

2.3.2. Structure of Clay Minerals

Clay minerals belong to layer or sheet silicates (phyllosilicates). Phyllosilicates have a soft, platy, or scaly structure. Sheets and scales have a flexible or even plastic structure. These characteristic features of phyllosilicates are acquired through the infinite extension of the silica-oxygen sheet in the structure [31]. A clay mineral's structure primarily consists of two building blocks. One is the tetrahedral unit, known as the silica tetrahedron, and the other is the octahedral unit, known as the alumina octahedron [32].

The Tetrahedral unit is formed as each silicon atom is surrounded by four oxygen atoms, and it is the most fundamental unit in clay structures with a chemical formula of SiO4-4. Silicon cations arranged tetrahedrally connect to each other through sharing oxygen, with the bases of the tetrahedral units in the same plane, forming a strong covalent bond [29]. The Octahedral unit consists of six oxygen or hydroxyl atoms attached to each aluminum or magnesium cation. The structure, with a chemical formula of $AlO^3(OH)^{36-}$, features units combining at their corners to form the alumina layer, ensuring that their surfaces are in the same plane. Various cation types can be found in the octahedral layer, including Al, Mg, Fe^{+2}, and others. Additionally, Fe, Ti, Ni, Zn, Cr, and Mn may be present [33].

The alumina layer can exist in two forms: trioctahedral and dioctahedral, depending on whether the octahedron is filled entirely or in two-thirds. To maintain charge balance, only two-thirds of the octahedra in the alumina layer have aluminum (Al^{3+}) ions at the center, with the remaining portion being vacant. This situation results in the formation of a dioctahedral (double regular octahedral) structure. When magnesium (Mg^{2+}) replaces aluminum as the central ion in every octahedron (i.e., when each octahedron is fully occupied), a trioctahedral structure (triple regular octahedral) is formed (Chitnis and Mohan Sharma, 1997) (Figure 1.1) [34].

Clay minerals are formed by the arrangement of numerous aluminum and silica layers side by side and on top of each other, with oxygen ions binding them together. By repeatedly connecting tetrahedral and octahedral layers, two-layered clay minerals (1:1 or TO structure) are formed, and three-layered clay minerals (2:1 or TOT structure) are created through periodic repetition, with one octahedral layer sandwiched between two tetrahedral layers [35].

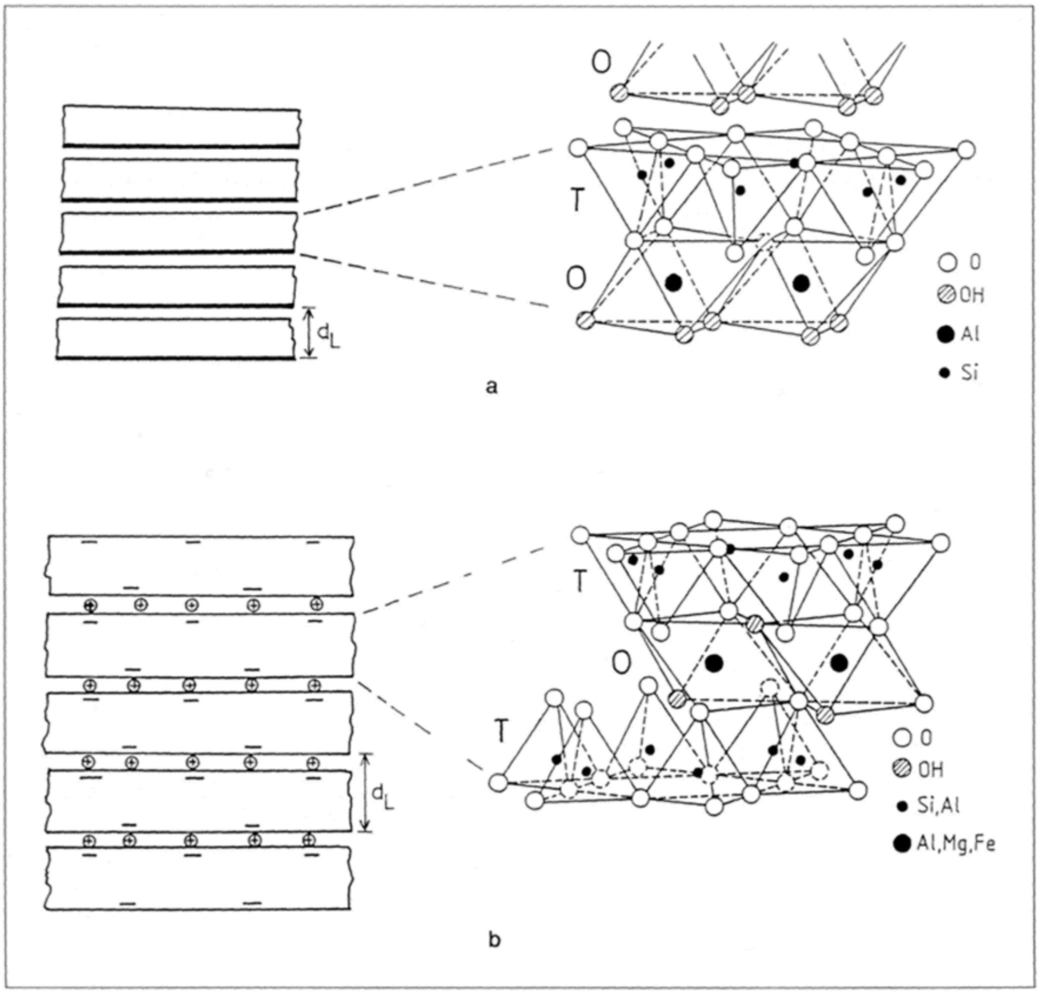


Figure 0.1. Clay minerals (a) Bilayered (1:1 or TO); (b) Trilayered (2:1 or TOT)

In TO (1:1 or two-layered) clay layers, oxygen atoms belonging to the tetrahedral layer form oxygen planes on the upper surface of the layer. On the lower surface of the layer, oxygen atoms belonging to the octahedrons (O) with exposed negative charges create an oxygen-hydrogen (O-H) plane. When two two-layered layers stack on top of each other, hydrogen bonds (O-H-O) form between the oxygen atoms of the tetrahedra and the hydroxides of the octahedra. Consequently, it becomes challenging for molecules like water to penetrate between the layers, and the layers cannot separate significantly.

In TOT (2:1 or three-layered) clay layers, oxygen planes are present on both sides of the layer due to the presence of tetrahedral layers on either side of the octahedral layer. When two three-layered layers stack on top of each other, oxygen planes are facing each other, and due to the absence of cations to bind the negatively charged oxygen ions together, the layers do not attract each other electrically. Therefore, in three-layered (TOT or 2:1) clay minerals, the gap between the layers can increase with the amount of drawn water, reaching up to 1.8 nm [36].

2.3.3. Classification of Clay Minerals

The octahedral and tetrahedral structures, taking on a plate-like shape, form a polymer structure together. The combination and arrangement of the formed plates lead to the emergence of different structures. Changes in the basic structure result in the formation of clay minerals. Different minerals arise from the displacement of cations in octahedral layers while maintaining the crystal structure. This situation, where cations in the environment are exchanged without changing the crystal structure, is defined as "isomorphous substitution." Due to the isomorphous substitution property, minerals have different structures and are described with different names [37]. In the classification of clay minerals, various criteria can be taken into consideration, such as crystal structure, layer thickness, interlayer distance, layer type, layer charge, the nature of interlayer material, ion content, layer arrangement, and organization. One of the most commonly used classifications is Grim's [29] classification of clay minerals based on layer type and charge (Table 1.1).

Table 1.1. Classification of clay minerals based on layer type and layer charge [29]

Type	Layer Charge	Group	Subgroup	Species
1:1 T.O	~0	Kaolinite-Serpentine	Kaolins	Kaolinite, dickite, nacrite, halloysite
			Serpentines	Chrysotile, lizardite, antigorite, amesite
2:1 T.O.T	~0	Pyrophyllite-Talc	Pyrophyllites	Pyrophyllite
			Talc minerals	Talc, willemseite

	~0.2-0.6	Smectite	Dioctahedral smectites/Montmorillonites	Montmorillonite, beidellite, nontronite
			Trioctahedral smectites/Saponites	Saponite, stevensite, hectorite, saponite
	~0.6-0.9	Vermiculite	Dioctahedral vermiculites	Dioctahedral vermiculite
			Trioctahedral vermiculites	Trioctahedral vermiculite
	~1	Mica	Dioctahedral micas	Muscovite, paragonite
			Trioctahedral micas	Biotite, phlogopite, lepidolite
	~1	Brittle Micas	Dioctahedral brittle micas	Margarite
			Trioctahedral brittle micas	Sybertite, xanthophyllite, clintonite, anandite
2:1:1 T.O.T.O	Variable	Chlorite	Dioctahedral chlorites	Donbassite
			Trioctahedral chlorites	Clinoclase, samarskite, nimite, pennantite

2.4. TRAVERTINES PRODUCTION and ENVIRONMENTAL EFFECTS

Travertine, a distinctive sedimentary rock created by mineral springs, is both beautiful and useful, making it a favorite building and decorating material. As demand for travertine develops, understanding its production techniques and accompanying environmental implications becomes vital. This in-depth investigation weighs the environmental effects of travertine manufacturing alongside the feasibility of implementing sustainable strategies [38].

Calcium carbonate creates travertine as spring waters rich in minerals are exposed to the elements. Travertine is formed when layers of sediment solidify over time, giving the rock its characteristic porous texture. The most common technique for mining travertine from the ground is called quarrying. Large blocks must be cut from quarries as part of the extraction process, a practice that can have serious consequences for the environment if it is not managed responsibly [39].

The quarrying of travertine can have a number of unintended consequences for the natural world. Many quarrying operations cause deforestation because vast swaths of land must be removed to get to the travertine deposits. The loss of biodiversity and the instability of soil are just two of the many ecosystem services that can be disrupted when natural habitats are destroyed. In addition, quarrying operations can cause air and water pollution, which has consequences for the surrounding area and the people who live there.

Because travertine is formed in tandem with mineral-rich spring waters, its manufacture is inherently water-intensive. To lessen the damage done to the environment by water extraction, sustainable water management methods are needed. Water recycling systems and other technologies that reduce water consumption should be implemented in quarries. As a result, less water is used in the manufacturing of travertine, which is good for the environment [17].

After being extracted from the ground, travertine is worked on in various ways. These operations require a lot of energy, typically from fossil fuels. High energy consumption has negative consequences on the environment, which can be mitigated if the industry adopts more energy-efficient practices and looks into renewable energy options like solar and wind power. The manufacturing of travertine can do its part in environmental responsibility by adopting sustainable energy techniques, which lower the sector's carbon impact [17].

Offcuts and sludge are just two examples of the waste produced during travertine production. The negative effects of these by-products on the environment can be mitigated by the use of sustainable waste management strategies. Recycling and reusing travertine debris can assist to resource efficiency, minimizing the demand for additional raw materials. Furthermore, travertine waste can be turned into a valuable resource through creative reuse in areas such as the creation of eco-friendly building materials or as a component in landscape architecture.

The quarrying of travertine frequently takes place close to human settlements. One of the most important parts of ethical quarrying and processing is communicating with and listening to these communities. Positive interactions between the travertine industry and the communities it serves can be encouraged through the implementation of corporate social responsibility activities like funding for local schools and hospitals. In addition to helping the local community, this method also helps ensure the long-term viability and widespread acceptability of the travertine industry [40].

Promoting sustainable practices within the travertine production industry is significantly aided by certification programs and regulatory frameworks. To ensure ethical and sustainable practices, businesses in this sector should comply with international norms such those established by the Forest Stewardship Council (FSC) and the ISO 14001 environmental management system. Adherence to rules and regulations is essential to the continued success of the travertine sector and the protection of natural resources [41].

To improve the sustainability of travertine manufacturing, further study and new ideas are needed. Further reduction of the industry's negative impact on the environment can be achieved by the investigation of other extraction methods, the creation of environmentally friendly processing technologies, and the discovery of novel uses for travertine by-products. Sustainable travertine production methods can be advanced by the combined efforts of academic institutions, businesses, and environmental groups.

Due to its distinct qualities and appealing aesthetic, travertine is now used in many different fields. However, the negative consequences on the ecology from travertine mining and processing just cannot be ignored. The travertine industry may help create a greener and more ethical future if it adopts sustainable practices, reduces its negative effects on the environment, and processes its stone in a responsible manner. Preserving the natural resources and habitats on which the travertine business relies is essential to its long-term viability, and so is striking a fair balance between economic growth and environmental responsibility [42].

2.5. UTILIZATION of TRAVERTINES

The aesthetic appeal, durability, and peculiar geological qualities of travertine, a unique form of sedimentary rock with distinctive porous structures, have led to its widespread use in a wide range of industries. This in-depth analysis looks at how travertines are used in a variety of contexts, from conventional building materials to cutting-edge green technologies [43].

The use of travertine in building structures is a traditional and widespread application of the material. Famous buildings, monuments, and temples have all been embellished with travertine because of the material's enduring aesthetic value. The Colosseum in Rome is built entirely of travertine, a material prized for both its durability and its classic beauty [44].

Travertines add a level of refinement and natural beauty to interior design. These stones are used for a variety of interior design projects, including flooring, wall cladding, and countertops, and they give any room a cozy, welcoming vibe. Because of their porous nature and earthy tones, travertines are a popular choice for individuals who want to bring the outside in.

Travertines have long intrigued artists and sculptors due to its adaptability and visual variety. The rock's intrinsic beauty and the ease with which it may be carved make it a perfect material for artistic expression. Travertines, which can be found all over the world, have long been used as a medium for artistic expression, from ancient monuments to cutting-edge installations [45].

For this reason, travertine is frequently used in landscaping and outdoor design projects. Travertine pavers, walkways, and pool decks not only improve the visual attractiveness of outdoor areas, but also have functional advantages. The porous quality of the stone enables for water absorption, leading to proper drainage and reducing surface runoff.

The porous nature of travertine makes stone ideal for use in fountains and other water features. A dynamic element is added to these installations by the stone's capacity to absorb and retain water, producing a visually intriguing play between water and stone. Water features constructed from travertine are frequently used as a focal point in the design of public places, gardens, and even private yards [46].

When it comes to restoring historical buildings, travertines are an essential component in protecting their original integrity. To ensure that new additions to ancient architecture blend in naturally with the old, it is common practice for restoration projects to source and use travertines that are close matches to the original materials. Travertines are used in modern building because of its practicality and aesthetic value. Travertines are a versatile building material that may be used for anything from exterior cladding to interior flooring to exterior facades. The use of travertines in modern architecture exemplifies the successful blending of old and new [47].

Beyond conventional uses, there is a growing interest in studying travertines as part of innovative sustainable solutions. Scientists and designers are exploring the potential of travertine as a green building material. Travertines are a potentially interesting material for use in passive cooling systems and energy-efficient design due to their porous nature and capacity to absorb and release moisture. Because of their porous structure, travertines can be used in geothermal systems. Travertine can be used as a heat transfer medium in geothermal heat exchange systems. This application exemplifies the versatility of travertines in novel energy-harvesting systems [48].

Soil conditioning with travertines has practical use in agriculture. Due to their high calcium carbonate concentration, travertines are useful additions for agricultural cultivation because they help maintain a consistent soil pH. To further aid in the upkeep of water quality in aquatic situations, travertines are also used as substrates in aquaculture. The exploitation of travertines encompasses a rich tapestry of applications, spanning from the conventional and historical to the creative and sustainable. Travertines have been used for centuries to decorate everything from ancient buildings to the canvases of contemporary artists. The innate beauty, resilience, and geological uniqueness of these sedimentary rocks continue to inspire architects, designers, and inventors across varied industries. Travertines are well-positioned to play a critical role in creating the visual and functional landscapes of our built environment as we move toward a future that focuses increased emphasis on sustainability and eco-conscious activities. The adaptability of travertines is a lasting tribute to the deep impact of nature's geological wonders on human creativity and ingenuity, as evidenced by their use in both historic architectural marvels and innovative sustainable solutions [49].

2.6. PROPERTIES of TRAVERTINES

With their distinctive porous structure and visually pleasant look, travertines are a sought-after material with a wide range of potential uses due to their impressive set of physical and mechanical capabilities. The geological beginnings, structural strengths, and practical implications that characterize the essence of travertines are revealed in this in-depth investigation.

2.6.1. Physical Properties

Travertines offer a compelling texture that varies from granular to fibrous, generating visually pleasing patterns. The interplay between calcite and aragonite crystals creates this roughness, which adds to the stone's distinctive appearance. Travertines can be found in a wide variety of colors, from soft beiges to rich rusts. Travertine deposits each have their own unique color due to the presence of impurities like iron oxides [17].

The porous structure of travertines is perhaps their most distinguishing physical feature. Calcium carbonate precipitates and dissolves in mineral-rich spring waters, giving rise to this characteristic. Because of this pore structure, travertine is an excellent choice for exterior uses where efficient control of moisture is critical. Complexity is added to the look of many travertines by veining. Veins are found running through a stone's surface because of the patterns formed by mineral differences and impurities. The artistic and decorative value of travertines is boosted by the natural veining that gives the stone its distinctive appearance [38].

2.6.2. Mechanical Properties

Because of its durability, travertines can be used in many building projects. The rock's general stability is due in part to the calcium carbonate crystals' ability to interlock with one another. Mineral content, contaminants, and the geological circumstances during formation can all affect how strong a travertine is. When assessing the stone's potential structural application, this quality is essential for architects and engineers to take into account [44].

Travertines' resistance to the effects of weathering and other environmental factors is due in large part to its mechanical feature of durability. Travertines are extremely durable because of their tight structure and the hardness of calcium carbonate crystals. Because of its resistance to weather and other environmental factors, natural stone is ideal for use in outdoor settings [17].

Travertine's resilience to freeze-thaw cycles is another evidence of the rock type's capacity to thrive in a variety of settings. The stone can absorb water through its porous nature without becoming weak. Because of this quality, travertine can be used outside even in climates where temperature changes cause some materials to expand and contract [44].

2.6.3. Thermal Properties

Travertine's performance can be affected in a number of ways due to its moderate thermal conductivity. Their propensity to transfer heat makes them an excellent choice for flooring in climate-controlled interiors. Travertine is a popular material for outdoor areas where heat absorption is a concern because of its thermal conductivity, which makes it feel cold to the touch [47].

Travertines, on the other hand, have excellent insulating characteristics due to their porous structure. Travertine is useful for temperature regulation because the air trapped within its pores acts as insulation. Due to its dual thermal capabilities, travertines can be used in a variety of applications [47].

2.7. CHEMICAL COMPOSITION of TRAVERTINES

The remarkable look, longevity, and geological significance of travertines can be attributed in large part to their unusual chemical makeup, making this interesting sedimentary rock a geological wonder. This research dives into the complex chemical composition of travertines, elucidating the minerals and chemicals that give them their distinctive qualities and make them a desirable material in a wide range of applications [38].

Calcium carbonate (CaCO3) is the primary chemical component of travertines and the main structural component of these sedimentary rocks. The bulk of travertines are mostly made of calcite, a crystalline type of calcium carbonate. Calcium carbonate is abundant in travertine, which gives the rock its characteristic hardness and plays an important role in the travertine's interactions with geological processes and its surrounding environment. Calcium carbonate deposited by mineral-rich spring waters is responsible for the formation of travertines. These waters dissolve calcium carbonate as they seep through limestone or other calcium-rich rock. Upon reaching the surface, the water loses its dissolved carbon dioxide, causing the calcium carbonate to precipitate and accumulate over time. The porous structure of travertines is formed in this way [41].

Although calcite is the most common mineral in travertine, the mineral make-up of travertine can vary. Travertines may also contain the crystalline calcium carbonate mineral aragonite. Certain travertines have a more see-through and banded structure due to the presence of aragonite relative to calcite, which can affect the rock's overall look [45].

Impurities and trace elements are common in travertine, giving the stone unique color and texture. For example, iron oxides can provide colors like beige and rust, whereas organic substances might make for darker shades. Overall mineralogical diversity in travertines can be affected by the presence of silica, alumina, and magnesium, which can increase the complexity of their chemical composition.

Travertines are permeable because of their chemical make-up. Travertines are able to absorb and release water due to their porous structure, which was formed during the precipitation process. Because of this quality, they can be used for outdoor paving and landscaping, two areas where good drainage is crucial [47].

Over time, weathering influences the chemical composition of travertines. In the presence of atmospheric agents like rain and carbon dioxide, calcium carbonate can dissolve. Travertines change throughout time in appearance because to chemical weathering, which modifies their surface texture and color in subtle ways. Travertines' chemical make-up can shed light on their formation's geological context. The water chemistry and climate of the past can be deduced by studying the mineralogy and trace element composition of travertines. As geological records, travertines contribute to our understanding of Earth's past and the dynamic interplay between minerals and water [44].

In order to evaluate the technical potential of travertines, knowledge of their chemical make-up is essential. For example, the rock's hardness and durability are affected by the amount of calcium carbonate present, making it more or less useful as a building material. When determining whether or not a given travertine is suitable for a given purpose, engineers and geologists take these characteristics into account. The chemical makeup of travertines varies depending on where they were formed. Travertines can be found all over the world, and each has its own unique mineral composition, hue, and feel. Due to their differences, all deposits offer a new geological canvas for engineers, artists, and scientists to experiment with [48].

The chemical composition of travertines is often analyzed using state-of-the-art analytical methods. Minerals in a rock can be identified using X-ray diffraction (XRD), while the elemental make-up can be determined using X-ray fluorescence (XRF). In conjunction with scanning electron microscopy (SEM), these methods allow scientists to decipher the tiny mineral tapestry of travertines. Finally, travertines' chemical make-up reveals an intriguing tale of geological events and environmental interactions. Calcium carbonate, mostly in the form of calcite, provides the basis for their distinctive qualities, including as hardness, porosity, and the capacity to transform over time. Each travertine deposit is a unique geological specimen due to the variations in mineral richness, impurities, and trace components that contribute to its visual variety [41].

Travertines are beautiful, but their chemical makeup is also important in many scientific fields. Understanding the complex link between minerals and their natural surroundings is facilitated by research into travertines, which has implications ranging from providing insights into Earth's past to impacting engineering decisions. Since travertines are prized in so many different fields, from architecture and the arts to geology and environmental science, their chemical make-up has long been the subject of study and admiration by those interested in the forces of nature that have shaped our planet [49].

2.8. CHEMICAL REACTIONS

Travertines, as intriguing sedimentary rocks, owe their distinctive features to a series of complex chemical reactions that occur over time. These reactions, primarily involving calcium carbonate ($CaCO^3$), play a fundamental role in the formation, transformation, and unique properties of travertines. This exploration delves into the chemical reactions that define the life cycle of travertines, encompassing their formation, interaction with the environment, and the implications for various applications [38].

The journey of travertines begins with the process of precipitation. In mineral-rich spring waters, calcium carbonate is dissolved from underlying limestone or other calcium-rich rocks. As these waters reach the surface and lose dissolved carbon dioxide, calcium carbonate undergoes a chemical reaction known as precipitation. This reaction leads to the deposition of calcium carbonate, forming layers of travertine over time.

In this reaction, calcium ions (Ca^{2+}) combine with bicarbonate ions ($2HCO_3^-$) to yield calcium carbonate ($CaCO_3$), carbon dioxide (CO_2), and water (H_2O) As shown in the equation (2.1). This fundamental precipitation reaction is the cornerstone of travertine formation.

$$\boldsymbol{Ca^{2+} + 2HCO_3^- \rightarrow CaCO^3 + CO_2 + H_2O} \tag{2.1}$$

The porous structure characteristic of travertines arises from a continuous cycle of dissolution and re-precipitation. As shown in the equation (2.2) over time, the surface of travertines can undergo chemical weathering due to exposure to environmental factors like rain and carbon dioxide.

$$\boldsymbol{CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-} \tag{2.2}$$

In this reverse reaction, calcium carbonate reacts with carbon dioxide and water to produce calcium ions and bicarbonate ions. The solubility of calcium carbonate in water allows for its dissolution and subsequent transport away from the rock surface. However, when these calcium and bicarbonate ions reach a new location within the travertine, the conditions may favor re-precipitation, leading to the continuous creation of the porous network within the rock [17].

The chemical composition of travertines extends beyond the fundamental calcium carbonate reactions, as impurities and trace elements contribute to the rock's coloration and mineral variations. As shown in the equation (2.3) Iron oxides, for instance, introduce varying hues from beige to rust, while organic matter may impart darker tones. The incorporation of silica, alumina, and magnesium diversifies the mineralogical composition, adding complexity to the overall chemical makeup of travertines. Travertines exist in a dynamic equilibrium with carbonate ions in aquatic environments. The solubility of calcium carbonate is influenced by factors such as temperature, pH, and the concentration of dissolved carbon dioxide. The carbonate equilibrium, expressed through chemical reactions, highlights the sensitivity of travertines to changes in environmental conditions [44].

$$\boldsymbol{CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}} \tag{2.3}$$

This reversible reaction illustrates the equilibrium between calcium carbonate and its dissociation into calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}). Variations in temperature and pH can shift this equilibrium, influencing the solubility and precipitation of calcium carbonate in travertines. Travertines, when subjected to anthropogenic influences, exhibit reactions with acids and alkalis. Acid rain, for example, contains sulfuric and nitric acids that can react with calcium carbonate in travertines, leading to their dissolution as shown in the next equation (2.4).

$$\boldsymbol{CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2} \qquad (2.4)$$

In this reaction, as appear in the equation (2.5) calcium carbonate reacts with sulfuric acid (H_2SO_4) to produce calcium sulfate ($CaSO_4$), water (H_2O), and carbon dioxide (CO_2). Conversely, exposure to alkalis may result in the transformation of calcium carbonate to calcium hydroxide.

$$\boldsymbol{CaCO_3 + 2NaOH \rightarrow Ca(OH)_2 + Na_2CO_3} \qquad (2.5)$$

This reaction with sodium hydroxide ($NaOH$) leads to the formation of calcium hydroxide ($Ca(OH)_2$) and sodium carbonate (Na_2CO_3).

The chemical reactions in travertines have significant implications for their engineering properties. The prevalence of calcium carbonate contributes to the hardness and durability of travertines, making them suitable for various construction applications. Engineers must consider these reactions when assessing the performance and long-term stability of travertines in different environments [47].

Analyzing the chemical composition of travertines involves sophisticated analytical techniques. X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) are commonly employed to unravel the intricate chemical tapestry at a microscopic level. These techniques provide valuable insights into the mineralogy, impurities, and trace elements present in travertines.

In conclusion, the chemical reactions associated with travertines underscore the dynamic interplay between calcium carbonate, the environment, and various external influences. From the foundational precipitation reactions that give rise to these sedimentary rocks to the continuous cycles of dissolution and re-precipitation shaping their porous structure, travertines epitomize the geological processes driven by chemistry [50].

Understanding the chemical composition of travertines not only enriches our appreciation of their aesthetic qualities but also holds practical significance in fields ranging from geology and environmental science to architecture and engineering. As a testament to nature's intricate chemical tapestry, travertines continue to captivate scientists, researchers, and enthusiasts alike, offering a glimpse into the profound and dynamic relationship between minerals and the ever-changing Earth.

CHAPTER 3

MATERIAL AND METHOD

In this study, 50% bentonite - 50% marl soil mixture was used. In laboratory studies, grain size distribution analyzes were first performed to determine the grain size distribution of the travertine powder and clay used in the experiments, and the grain size distribution of the materials is presented in Figure 3.1. Table 3.1 displays abbreviation samples used in the study along with natural bentonite. Before the analysis, the materials were laid, dried, and passed through Sieve No. 40 for testing. The sieving process was utilized to eliminate larger particles and contaminants that could compromise the reliability of the experimental results and guarantee a consistent particle size distribution. Studying the effects of travertine dust on soil properties has been made possible by using materials passing through the sieve. This has allowed for the acquisition of more reliable and meaningful findings. Also, the stabilizer's specific surface area and the soil's stabilizing effects are both improved when the proportion of fine material is higher [46]. The marerials and its abbreviations are listed below:

Table 0.1. The marerials and its abbreviations

Marerial	Abbreviation
Bentonite	B
Marl	M
Travertine	T
Potassium Hydroxide	KOH
Water	W

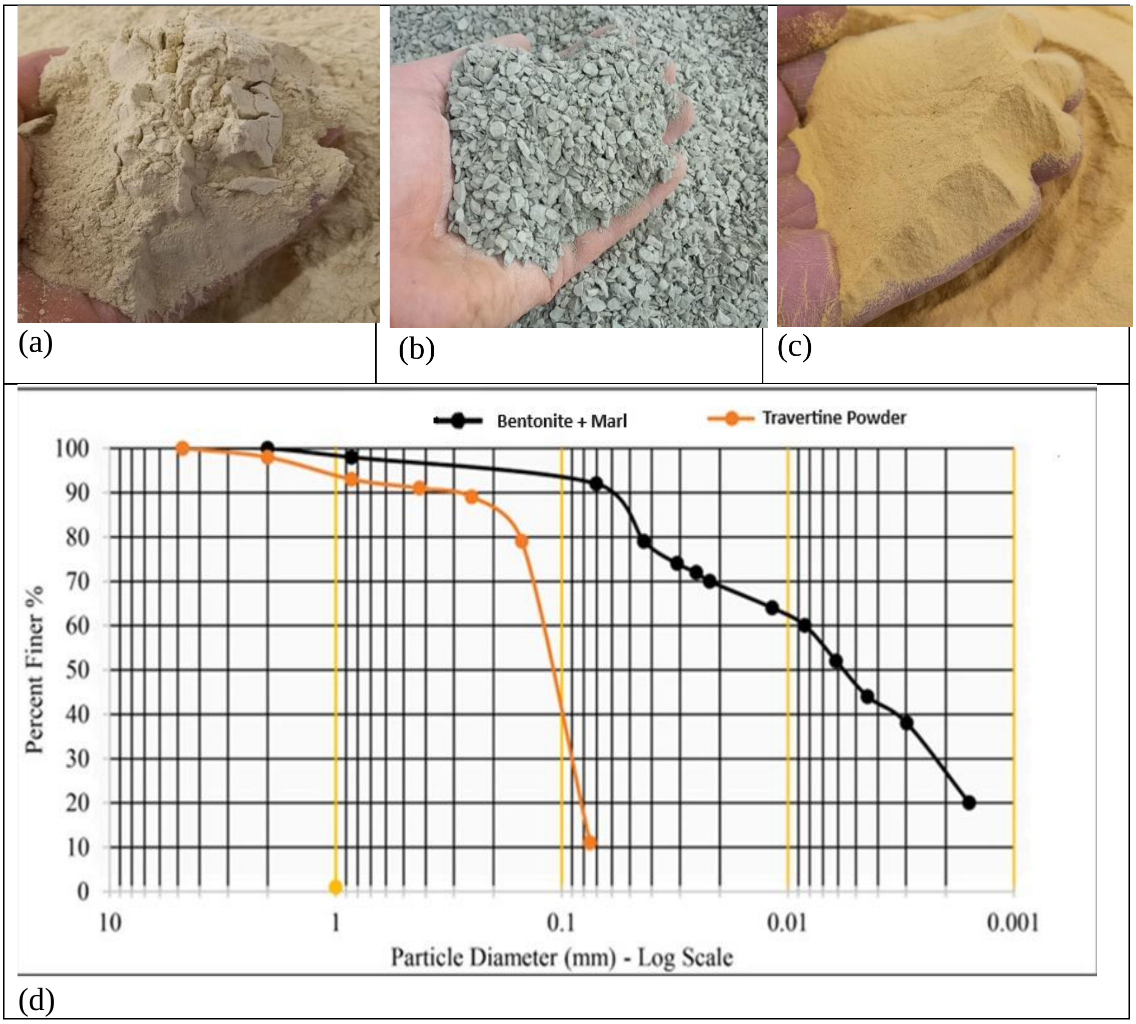


Figure 0.1. (a) Bentonite (b) Marl, (c) travertine powder. (d) Graphs showing the distribution of mixed Bentonite-Marl and travertine powder particle sizes [1].

3.1. MATERIAL

3.1.1. Bentonite

Bentonite samples (Figure 3.2) were collected from a zone in Tokat City, Turkey, for this research. A microscopic crystal structure is present in bentonite. The exceptional properties of bentonite, a type of clay, give it great value in many different sectors. To fully grasp its many uses, one must be familiar with its characteristics, functions, and significance.

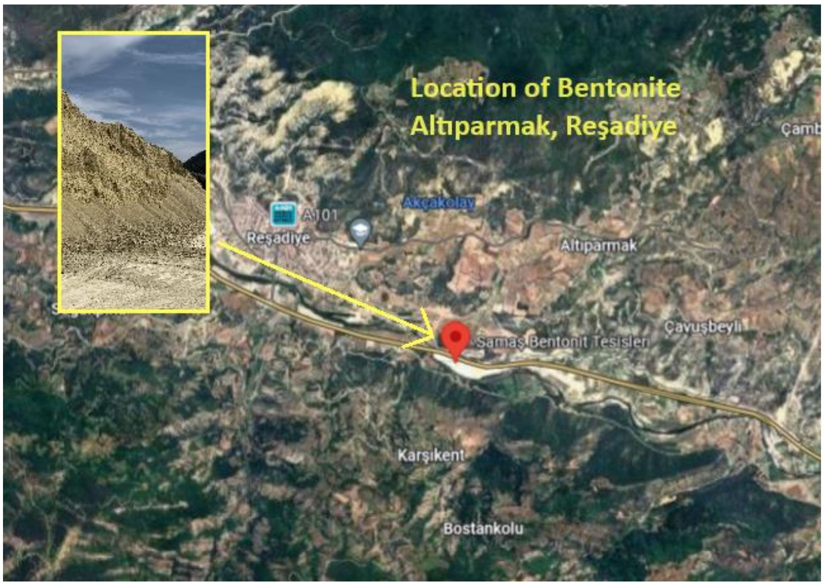


Figure 0.2. Bentonite site location

Montmorillonite minerals are characterized by their large surface area, high swelling potential, low hydraulic conductivity, and high cation exchange capacity. The results for the liquid limit value and plastic limit were 312% and 67%, respectively, as per ASTM D4318. Following the ASTM D698 standard, the standard proctor test on bentonite ground yielded a water content of 42% and a maximum dry unit volume weight value of 11.61 kN/m3 (Figure 3.3) [1].

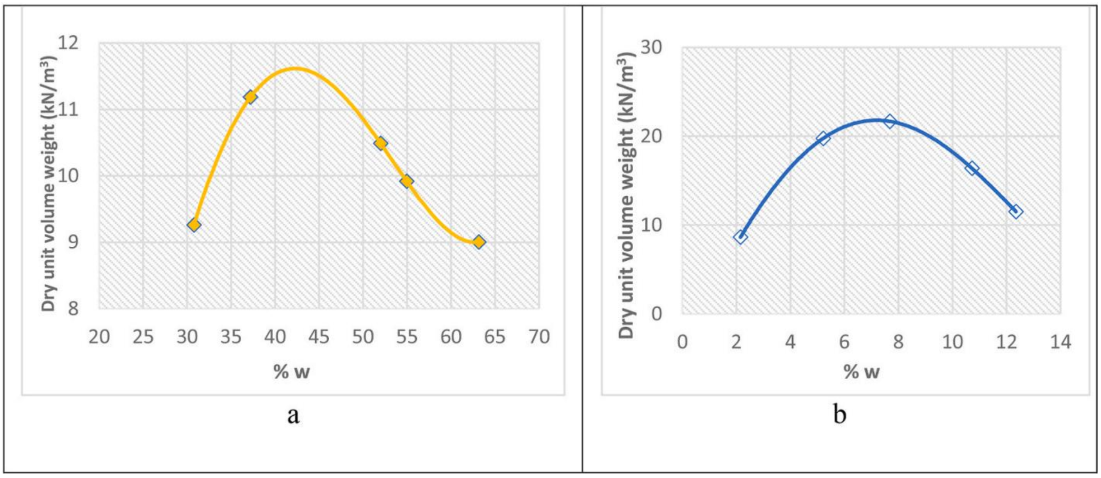


Figure 0.3. Optimum water content values and dry unit volume weight for bentonite (a) and travertine (b) [1].

Montmorillonite, a layered hydrous aluminum silicate, is the main component of bentonite, a very versatile clay mineral. Because of its structure, bentonite has a high cation exchange capacity (CEC) and an outstanding swelling capacity, which make it useful in many different contexts [9].

Its capacity to swell is one of bentonite's most striking characteristics. The particles of bentonite expand and create a gel-like substance when they are hydrated. This quality is especially useful in situations that call for sealing and plugging, like in civil engineering projects, landfill liners, and drilling muds for oil and gas exploration. Because of its swelling capacity, bentonite is also useful for regulating groundwater flow and blocking the migration of fluids in rock formations [15].

The high cation exchange capacity (CEC) of bentonite is an additional noteworthy quality of this material. Because of this quality, bentonite is used extensively in many different industries as a binder and adsorbent. Soil amendments and fertilizers made of bentonite enhance soil structure, water retention, and nutrient availability, which are important in agriculture. To lessen their negative effects on the environment and increase their effectiveness, pesticides and herbicides are carried by it.

The cosmetics, pharmaceutical, and food industries can all benefit from bentonite's excellent colloidal properties. In food processing, pharmaceutical formulations, and personal care products, it serves as a thickener, stabilizer, and suspending agent. Because of their all-natural composition and low risk of side effects, bentonite-based products find extensive application in cosmetics, pharmaceuticals, and even food additives [19].

Bentonite plays a significant role in waste management and environmental remediation. It is highly recommended for enclosing ponds, polluted sites, and landfills due to its capacity to contain pollutants and reduce groundwater contamination. Environmental protection for the long term is guaranteed by barriers made of bentonite, which effectively stop harmful substances from seeping into the environment.

In geotechnical engineering and building projects, bentonite is an essential component. Incorporating it into drilling fluid improves stability, lubrication, and pressure control in the borehole. Engineers working on foundations and soil stabilization often use slurries and grouts made of bentonite to lessen the likelihood of liquefaction, improve soil properties, and decrease seepage.

Bentonite, a clay mineral, has many different uses and characteristics. Oil and gas, cosmetics, pharmaceuticals, food processing, environmental remediation, construction, and a host of other industries rely on it due to its colloidal properties, high CEC, swelling capacity, and natural abundance. If we want to make the most of bentonite in all its forms, we need to know what it is, how it works, and why it's important [9].

3.1.2. Marl Soil

The unique characteristics of marl soil, a sedimentary deposit made up of clay and calcium carbonate (CaCO3), determine its value and utility in a wide range of contexts. In order to make the most of marl soil in environmental, agricultural, and constructional settings, it is crucial to have a good grasp of its properties, applications, and relevance (Figure 3.4).

Figure 0.4. Marl soil location

Because of its variable proportions of calcium carbonate and its intermediate texture—which can be anything from clayey to silty—marl soil is easily identifiable. Because of its unusual makeup, marl soil has a number of desirable characteristics that influence its use and performance. The high nutrient and fertility levels of marl soil are two of its most distinctive features. Soil fertility and plant development are both enhanced by the presence of calcium carbonate, which supplies magnesium and other vital nutrients. Because of their high nutrient and organic matter content, marl soils are ideal for farming. Farmers frequently cultivate pasture and forage crops, as well as grains, veggies, and fruits, on marl soils. Soil amendments, irrigation, and fertilization are some of the best management practices that can increase the fertility of marl soil [39].

Because of its clayey texture and high calcium carbonate content, marl soil also has a good ability to retain moisture. This quality is useful in agriculture because it keeps soil moist and lessens the impact of water stress on crops, which is especially important in dry and semi-arid areas. Marl soils that can hold enough water are better able to prevent drought and waterlogging, making them ideal for growing plants. The engineering qualities of marl soil also make it an excellent choice for building and civil engineering endeavors. Road embankments, foundation backfills, and earthworks benefit greatly from its compressibility and cohesiveness, which facilitate compaction and stabilization. In infrastructure projects, marl soils are frequently utilized as fill material for building foundations and retaining structures because they are cost-effective [41].

The alkaline pH and calcium carbonate content of marl soil affect soil chemistry and nutrient availability. Although some crops may struggle with soils that are too alkaline, liming and pH adjustments are two examples of good soil management practices that can help. Furthermore, marl soils help regulate the climate and sequester carbon dioxide by storing the gas in calcium carbonate, which reduces emissions of greenhouse gases and slows the rate of climate change.

The management of land and preservation of the environment are affected by marl soil. Because of its inherent qualities, it can be used to restore and restore deteriorated land, such as former agricultural fields, mine sites, and quarries. Contributing to sustainable land use practices and ecosystem resilience, marl soils can restore ecosystem functions, improve soil structure, and enhance biodiversity [43].

Soil marl is an invaluable resource with many uses in farming, building, and ecological restoration. It is a multipurpose substrate due to its environmental benefits, engineering qualities, fertility, and capacity to retain moisture. In order to ensure the long-term viability of marl soil, stakeholders must have a thorough understanding of its properties, uses, and significance for sustainable land use planning, agricultural productivity, infrastructure development, and environmental stewardship. Stakeholders can maximize the benefits of marl soil while minimizing its environmental impacts by utilizing its potential and adopting appropriate management practices [38].

3.1.3. Travertine Properties

Imanlar town waste from travertine quarries in Eskipazar, Turkey (Figure 3.5), provided the travertine samples utilized as study additives. The study's travertine powder primarily consists of the calcite ($CaCO3$) mineral. Although calcite is composed of 95% calcium carbonate, it also contains another compound by mass, as shown in Table 3.2 [1].

Figure 0.5. Travertine quarries in Eskipazar, Turkey

Table 0.2. The fundamental properties of bentonite and travertine powder used in the study [1].

Definition	Traverteine Powder (mass%)	Bentonite (mass%)	Bentonite-Marl (mass%)
MgO	0.6597	2.10	2.3676
SiO_2	0.4105	61.28	56.5458
CaO	95.1862	4.54	13.8296
Fe^2O_3	3.3675	3.01	6.5522
SrO	0.3771		0.1941
Al_2O_3		17.79	16.9319
K_2O		1.24	2.4841
Na_2O		2.70	
Liquid Limit	21.54	312	
Plastic Limit	15.12	67	
Activity		8.75	

The average natural unit volume weight (γ) was determined as 25.05 kN/m^3 with the experiments performed on the travertine samples. Liquid limit and plastic limit of travertine powder were determined as 21% and 15%, respectively, according to ASTM D4318. By following ASTM D698, the standard proctor test ASTM D698 was conducted on the travertine powder samples, and the test results are shown in

Figure 3.4. As a result of the experiments, the optimum water content (ωopt) was found to be 7.1% and the maximum dry unit volume weight value (γkmax) was found to be 20.89 kN/m3 . The direct shear test was also carried out in this study on travertine powder samples in accordance with ASTM D3080-04 at optimum water content. As a result of the experiments, the internal friction angle value (Ø) was found to be 28.15◦ and the cohesion value (c) was found to be 19.17 kN/m3 [1].

Based on the experiments conducted on the travertine samples, the average natural unit volume weight (γ) was found to be 25.05 kN/m3. In accordance with ASTM D4318, the liquid limit for travertine powder was found to be 21% and the plastic limit to be 15%. Figure 3.4 displays the results of the standard proctor test ASTM D698 that was performed on the travertine powder samples in accordance with ASTM D698. The experiments yielded the following results: a water content of 7.1% was determined to be optimal, and a maximum dry unit volume weight value (γkmax) of 20.89 kN/m3 was determined. At the optimal water content, this study also conducted the direct shear test on travertine powder samples according to ASTM D3080-04. The experimental results showed that the cohesion value (c) was 19.17 kN/m3 and the internal friction angle (Ø) was 28.15◦ [1].

3.1.4. Sand

The sand layers serve to facilitate drainage and minimize excessive pore water pressure during the test, similar to the role of porous stone in the traditional free swelling test. Granular sand, which consists of minutely divided rock and mineral particles, is among the planet's most plentiful natural resources. Its versatility and exceptional qualities make it an indispensable part of many different kinds of products and services, as well as our daily lives. In order to fully grasp the significance of sand in environmental, agricultural, construction, and manufacturing settings, it is essential to have a solid grasp of its properties, applications, and value (Figure 3.6). The composite clays were placed between two layers of sand, each 50 millimeters thick. These sand layers were densely packed at the highest dry unit weight and optimum moisture content to prevent unwanted settlements during the compaction of the composite clays.

Figure 0.6. Sand

Sand is useful and versatile in many different contexts because of its unique characteristics. The characteristic particle size distribution of sand, which usually falls between 0.0625 and 2 millimeters in diameter, is one of its most striking features. Sand is perfect for use in filtration systems, drainage layers, and building materials due to its granular texture, which gives it excellent drainage and permeability characteristics.

In addition, sand typically contains minerals like feldspar, calcite, and quartz, which give the material unique physical and chemical characteristics. As an example, quartz sand is ideal for abrasive blasting, glassmaking, and hydraulic fracturing (fracking) due to its high silica content and hardness. Because of their fluxing characteristics and low melting point, feldspar-rich sands find widespread use in the ceramics and pottery industries. In contrast, calcite sand is widely utilized in construction, water treatment, and soil amendments due to its high calcium carbonate content.

3.2. METHOD

For many environmental and engineering purposes, knowing how clay mixtures swell is essential. In this study, the swelling behavior of clay mixtures stabilized with travertine was investigated using a comprehensive methodological approach. Examining how well deep and shallow mixing techniques mitigate swelling potential and improve soil stability was the primary goal of the study.

3.2.1. Initial Testing and Characterization

Basic geotechnical tests were conducted in accordance with ASTM standards, including compaction tests, liquid limit and plastic limit tests, sieve analysis, and free swelling tests. The study aims to comprehend the mechanical properties and swelling behavior of clay soils treated with travertine, while also considering the influence of KOH. Initial laboratory testing focused on characterizing the clay mixtures' compaction properties. After conducting compaction tests (Figure 3.7), it was determined that 20% moisture was the ideal level for the soil mixture. By guaranteeing uniform circumstances for sample preparation, this preliminary step set the stage for following experiments.

Figure 0.7. The manual compaction device

The base soil, which is a 50:50 mixture of bentonite and marl soil, was subjected to liquid limit (Figure 3.8) and plastic limit tests after compaction testing. The results of these tests were very helpful in characterizing the soil's behavior under different moisture conditions, as they shed light on its plasticity and consistency. The effect of travertine on the soil's swelling behavior could also be studied by adding varying percentages of the stone (5%, 10%, 15%, and 20%).

Figure 0.8. The liquid limit device

3.2.2. Swelling Experiments

Swelling experiments utilizing both small-scale and large-scale devices were the next step in the research. Samples made with varying amounts of bentonite, marl, and travertine were swelled under controlled circumstances in the small-scale swelling apparatus (Figure 3.9).

Figure 0.9. Small-scale swelling device

Soil expansion reduction effects of different travertine contents over time could be studied in this way. While this was going on, the study's large-scale swelling device (Figure 3.10) shed light on the soil mixtures' long-term swelling behavior.

Figure 0.10. Large-scale swelling device

Concurrent with the swelling experiments, the compressive strength of the clay mixtures at various curing times was evaluated using unconfined compression tests (UCTs) (Figure 3.11). In order to track the change in strength over time, samples were tested at1,7,14,28,56, and 90 days intervals. Researchers were able to examine the connection between swelling behavior and mechanical properties thanks to this extensive testing regime, which provided useful information for engineering design and construction.

Figure 0.11. Unconfined compression device

In both the small-scale and large-scale swelling devices, sand, geotextile, and the prepared soil mixture were layered as part of the experimental setup. Swelling tests were conducted under conditions of uniform loading and drainage thanks to this setup, which reduced the influence of any confounding variables.

3.2.3. Comparative Analysis and Modification

Comparative analysis across samples and experimental setups was also made easier by including consistent proportions of travertine in the soil mixtures.

In addition, the second experimental model included a mid-layer modification that included 15% travertine in the bentonite-marl mixture. Soil stabilization and swelling reduction were the intended outcomes of this adjustment, which sought to evaluate the effect of shallow mixing. In order to understand how various stabilization techniques can reduce swelling potential, the study compared the results of shallow and deep mixing methods.

Swelling behavior of clay mixtures stabilized with travertine was thoroughly investigated in this study thanks to the methodology used. We learned more about the factors that affect soil stability and how to mitigate swelling with each step—from testing in the lab to experiments with swelling and analysis of mechanical properties. This study's results stress the significance of well-informed decision-making in soil stabilization projects and have consequences for geotechnical engineering, building practices, and environmental management. The sample ID and percentage of the mixed materials are presented in Table 3.3.

Table 0.3. The percentages of marerials

Sample ID	**Marl**	**Bentonite**	**Travertine**	**Potassium Hydroxide**	**Water**
MB	50%	50%	0%	0%	200 ml
MB5T	47.5%	47.5%	5%	0%	195 ml
MB10T	45%	45%	10%	0%	193 ml
MB15T	42.5%	42.5%	15%	0%	185 ml
MB20T	40%	40%	20%	0%	180 ml
MB5T KOH	47.5%	47.5%	5%	1M	195 ml
MB10T KOH	45%	45%	10%	1M	193 ml
MB15T KOH	42.5%	42.5%	15%	1M	185 ml
MB20T KOH	40%	40%	20%	1M	180 ml

The process of the expirment is shown in the Figure 3.12.

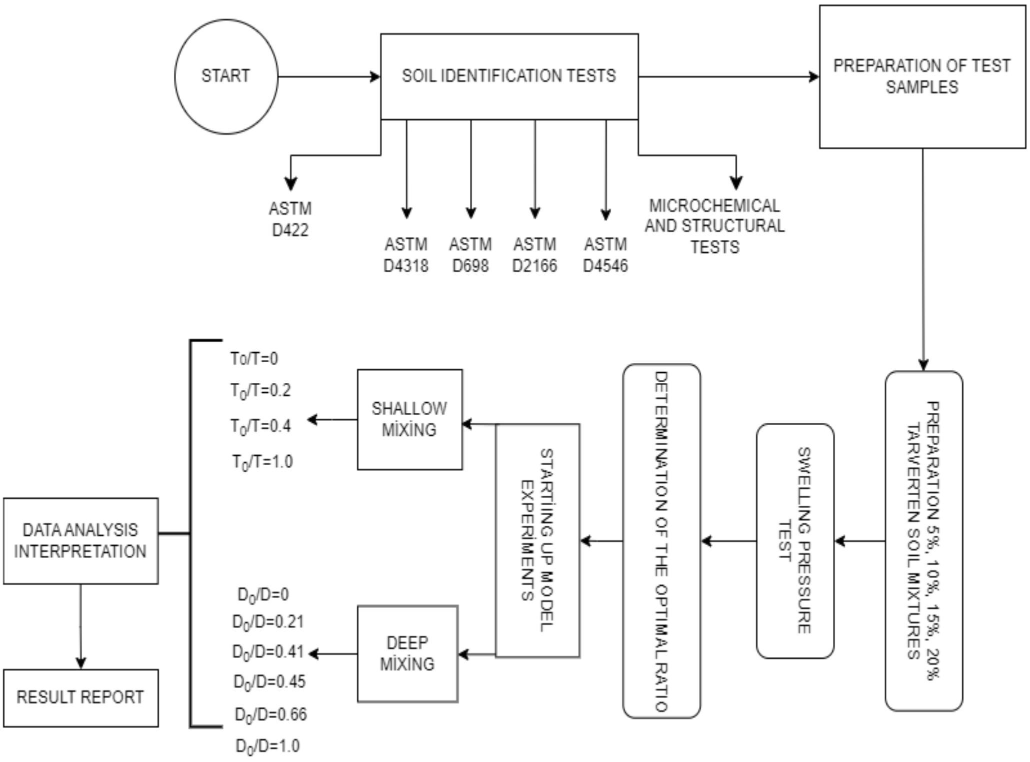


Figure 0.12. The process of the expirment

CHAPTER 4

RESULTS AND DISCUSSION

The objective of this chapter is to discuss and analyze the results derived from the experiments conducted on the clay samples. The chapter first focuses on the identification of the clay soils by measuring the fundamental soil properties, grain size distribution, Atterberg limits, specific gravity, optimum moisture content, maximum dry density, and soil swelling potential. And then discussed the results of the experiment of the model for understanding the behavior of the untreated and stabilized soil in shallow and deep condtions. The chapter contains the following parts:

- Investigation and discussion of the fundamental characteristics of clay soil.
- Investigation and discussion of the swelling behavior through swell pressure test, encompassing different additives and with varying in curing time.
- Investigation and discussion of the results of the pure soil and stabilized soils using an experimental model to understand the swelling behavior of travertine and travertine activated with NOH with an effect of the deep and shallow conditions, the analysis also consider the influence of the curing time.

4.1. GRAIN SIZE DISTRBITUION

The mechnical sieve analysis based on ASTM D6913 was first conducted for the soil’s samples, all the soils passed through sieve No. 200 and then hydrometer test was carried out based on ASTM D7928. The results demonstrate that the soil contains 65% clay and 35% silt.

4.2. ATTERBERG LIMITS

Liquid limit (LL) is defined as the moisture content at which a soil transitions from a plastic to a liquid state, while the plastic limit (PL) represents the moisture content below which the soil loses its plasticity and crumbles when molded, indicating its tendency to behave as a solid. The plasticity index (PI), calculated as the numerical difference between the liquid and plastic limits, ndicating greater deformability and volume change in response to variations in moisture content. The consistency test based on ASTM 4318 of the collected samples was implemented to determine the liquid (LL), plastic limit (PL). and plasticity index (PI). The results of liquid limit of pure soil are shown in Figure 4.1 with liquid limit LL = 106, plastic limit (PL) 34.53, and plasticity index (PI) 87.47.

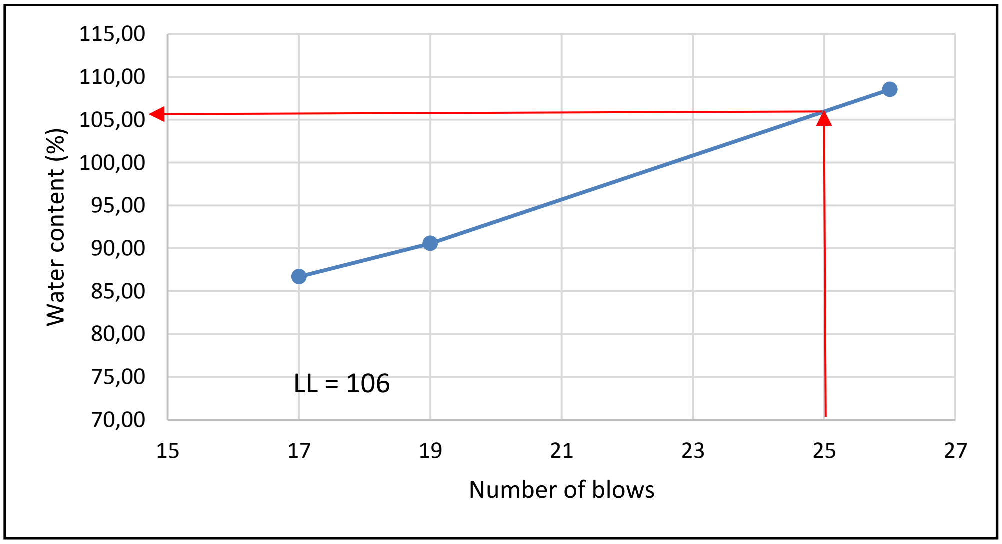


Figure 0.1. The results of water content versus of blows (LL) MB

The results of liquid limit (LL), plastic limit (PL) and plasticity index (PI) of percentagtges of (MB, MB5T, MB10T, MB15T, and MB20T) are summarized in Table 4.1 and the curves of these results are presented in Figure 4.2 and appendix 1.

Table 0.1. The results of liquid limit (LL), plastic limit (PL) and plasticity index (PI) of percentagtges of (MB, MB5T, MB10T, MB15T, and MB20T)

Sample #	LL	PL	PI
MB	106	34.53	87.47
MB5T	72	40.69	31.31
MB10T	71	36.55	34.45
MB15T	73	31.44	41.56
MB20T	71	31.44	39.56

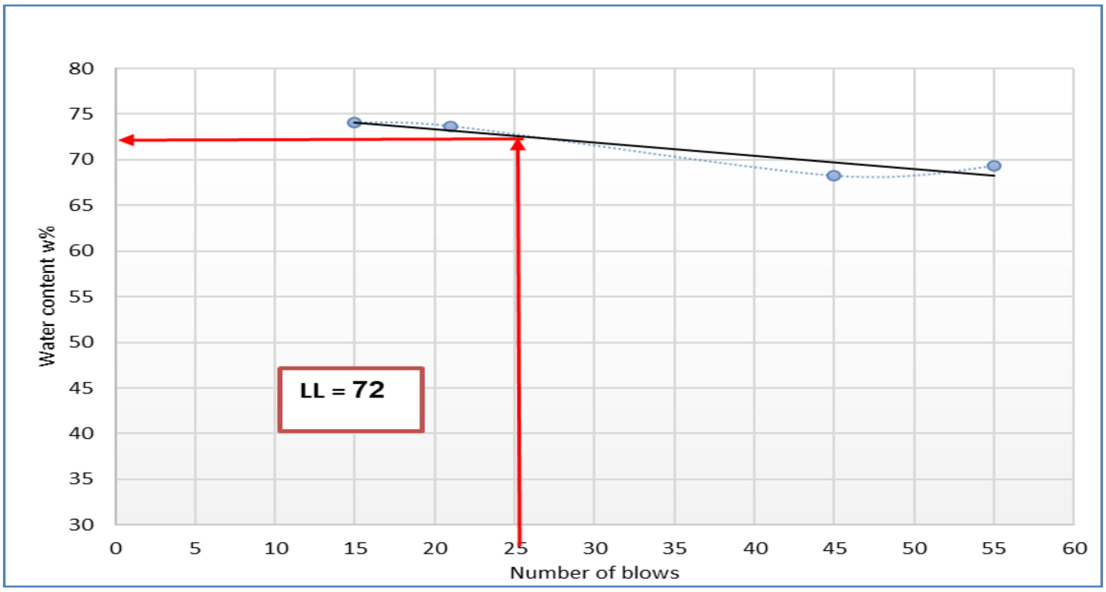


Figure 0.2. The results of water content versus of blows (LL)

4.3. COMPACTION

The Standard Proctor compaction test (ASTM D698-12) was performed on both untreated and treated soil samples to determine their optimal moisture content (OMC) and maximum dry density (MDD). The test was conducted on untreated soil (MB) and resulted in an MDD of 1.73 gr/cm³ and an OMC of 20%. The test was then repeated on a series of treated soil mixtures (MB5T, MB10T, MB15T, and MB20T) containing increasing amounts of bentonite. Figure 4.3 summarizes the results, which indicate that as the bentonite content increases, the OMC decreases, while the MDD increases. A comprehensive summary of all compaction test results is presented in Figure 4.3 and Table 4.2.

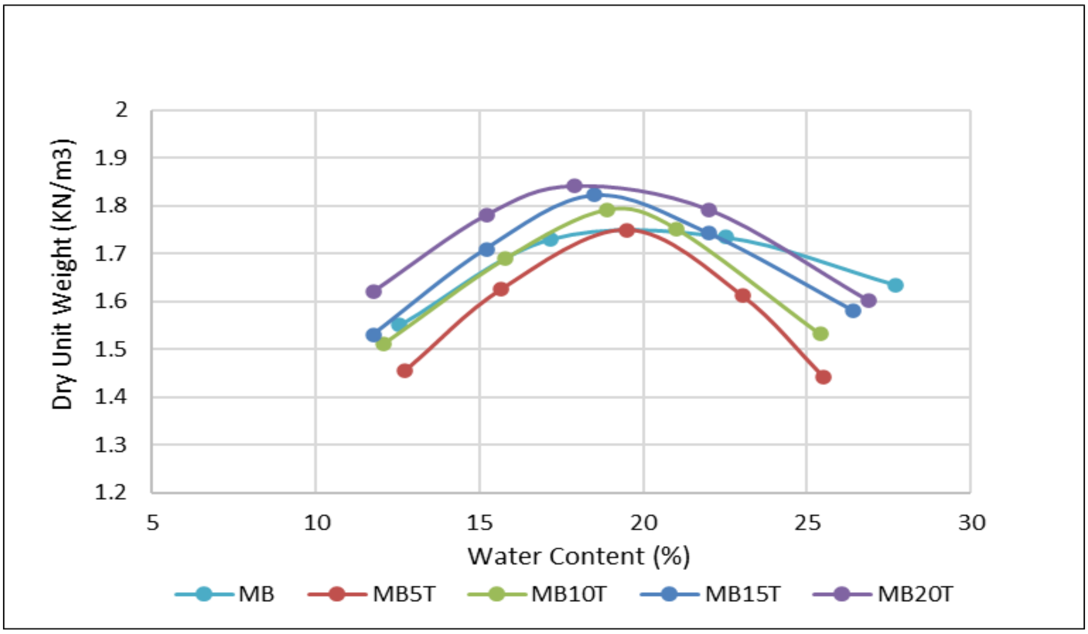


Figure 0.3. A comprehensive summary of all compaction test results

Table 0.2. A comprehensive summary of all compaction test results

Sample name	Maximum Dry density (MDD) (gr/cm³)	Optimum mositur content (OMC) (%)
MB	1.73 gr/cm³	20%
MB5T	1.75 gr/cm³	19.5%
MB10T	1.80 gr/cm³	19.3%
MB15T	1.83 gr/cm³	18.5%
MB20T	1.86 gr/cm³	18%

4.4. UNCONFINED COMPRESSIVE STRENGTH

The process of conducting a soil test involves collecting undisturbed samples, preparing them to maintain their integrity, conditioning them to stabilize moisture content and temperature, setting up the testing apparatus, measuring the sample dimensions, applying axial load, recording load and deformation data, determining the unconfined compressive strength (UCS), and analyzing the test data. The ultimate compressive strength (UCS) of the soil is determined by identifying the peak load sustained by the soil sample before failure. The test data is then compared with engineering standards or project requirements to assess the suitability of the soil for specific applications. A comprehensive report is prepared to document the testing procedure, experimental data, results, and any deviations from standard procedures and the test was conducted using ASTM D2166 for all soil samples.

4.4.1. Samples Without KOH

Figure 4.4 shows the effects of T and KOH-activated T addition on the UCS of soil samples, considering both setting time and additive rates. In this study Unconfined Compressive tests were applied to MB - MB5T - MB10T - MB15T - MB20T samples without KOH at curing times of 1, 7, 14, 21, 28, 56, and 90 days. The increase in the strength of the samples depending on the curing time is remarkable. The UCS of the treated sample increased by 6% after only 1 day of curing for 10% mixing ratio compared to the untreated sample. A slow and gradual increase in compressive strength was determined for the additive ratios between 7 and 14 days and 14 and 28 days of curing, respectively. The compressive strength recovery rate of the samples also confirmed the effects of curing time, where a gradual increase in the strength of the samples was determined with increasing curing time. The UCS of the T-treated marl sample after 28 days of hardening was measured as 315 kPa for 15% and 324 kPa for 20%. While the UCS improvement rate of T additive for 28 days of cure is 47.35% with 15% additive, this rate is 51% with 20% additive. It has become 40. (Figure 4.5). It would not be a mistake to consider the optimum curing time for this material as 28 days and the mixing ratio as 20%. However, the results of the 15% contribution rate in 28 days should not be ignored.

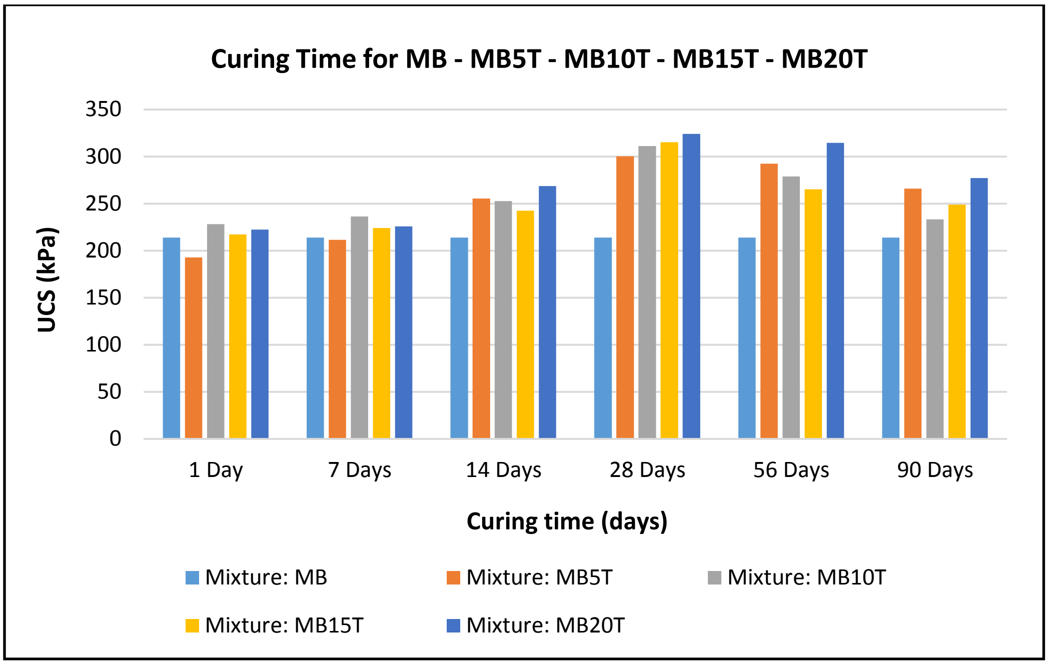


Figure 0.4. Curing Time for MB - MB5T - MB10T - MB15T - MB20T

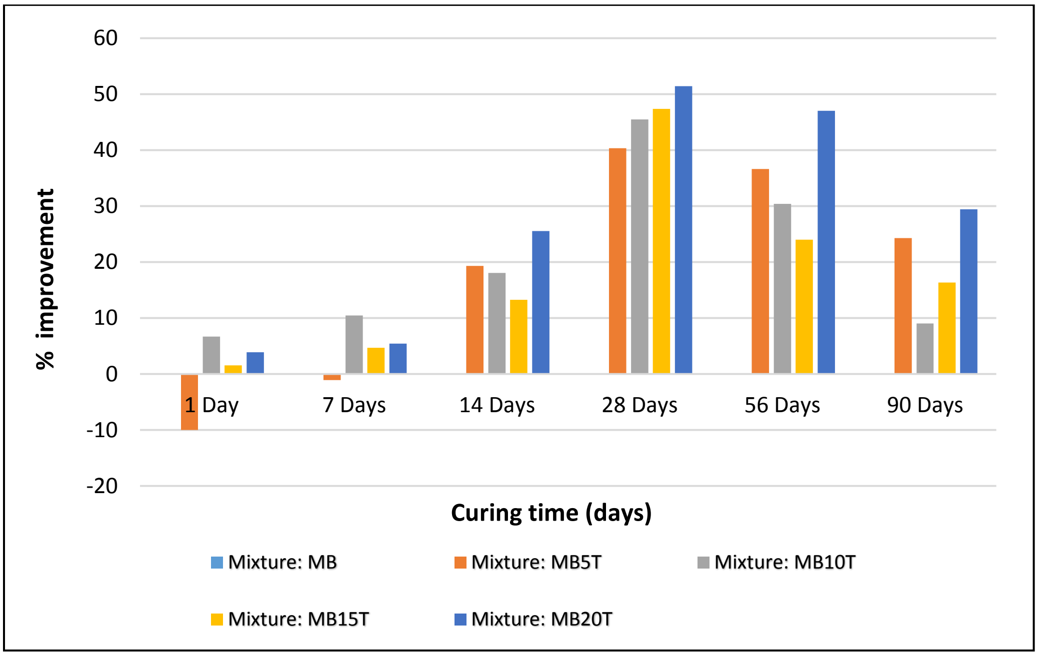


Figure 0.5. Curing Time for MB - MB5T - MB10T - MB15T - MB20T

Stress versus strain curves for all MB - MB5T - MB10T - MB15T - MB20T samples without KOH at 1 - 7 - 28 – 56 and 90-day curing time are shown in Figure 4.6. In general, it is possible to say that more strain softening is observed in stabilized samples and therefore there is more ductile behavior for stabilized samples.

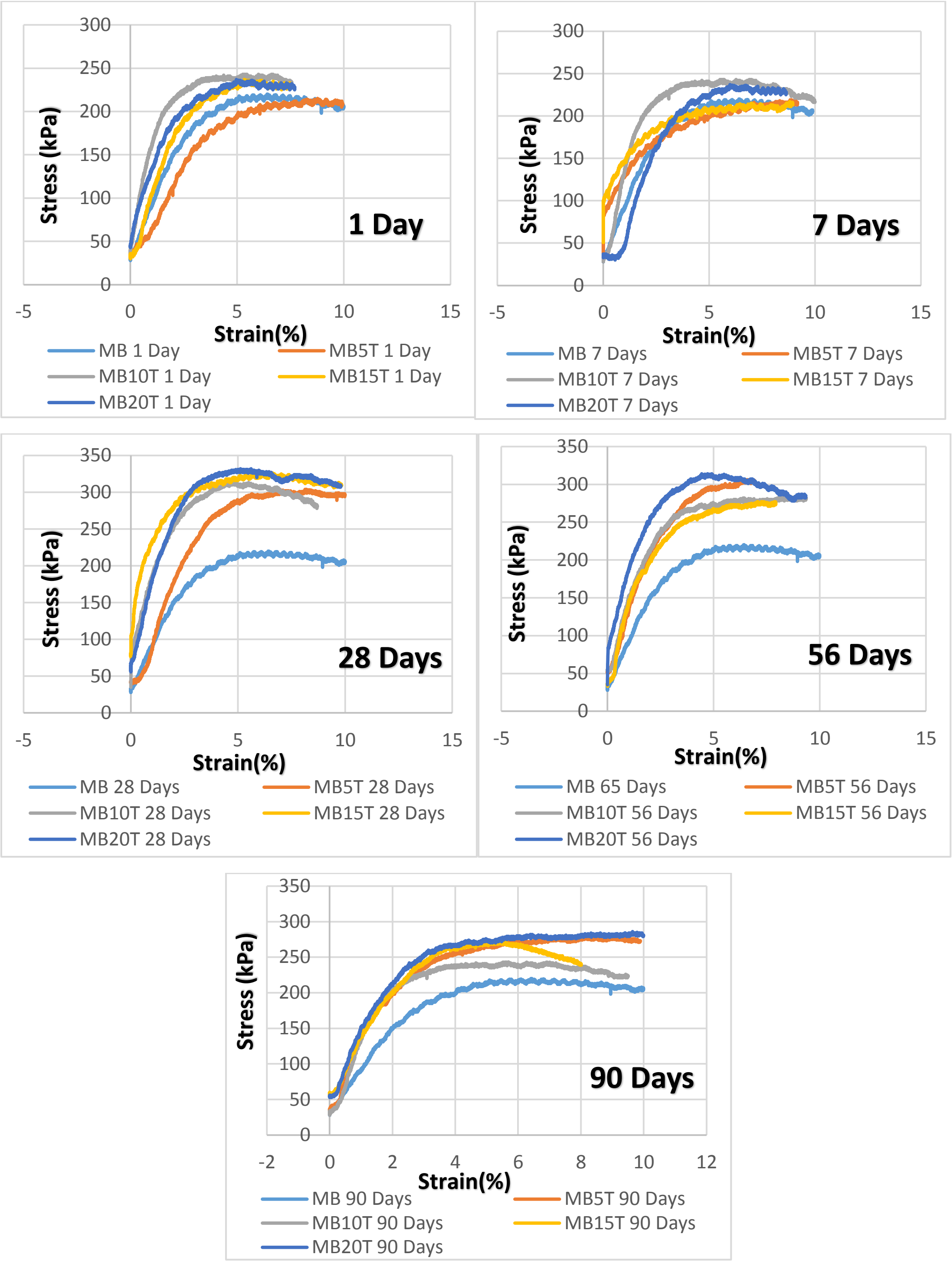


Figure 0.6. Unconfined Compressive tests of samples without KOH at 1 – 7 - 28 – 56 and 90 days curing time

4.4.2. Samples With KOH

The change of UCS of KOH-activated T added Marl soils with changing additive content after 7 days of curing is shown in Figure 4.7. UCS (Unlimited Compressive Strength) values in KOH added samples showed a consistent increase with increasing curing time in MB5T, MB10T, MB15T and MB20T as shown in Figure 4.8. A significant increase in soil strength was also measured by increasing the T content activated by 1 mol KOH. When the strength of untreated samples was compared to the strength of unstabilized samples for the optimum cure period of 28 days, 77%, 95%, 90% and 89% strength increase rates were observed with the addition of 5%, 10%, 15% and 20% T-KOH. (Figure 4.8). Curing time is an important factor in terms of the effect of KOH-T content on strength, and a significant increase was observed in all mixing ratios on the 28th day. However, after the 28th day, although there was an increase in strength compared to the pure sample, a relative decrease began. Therefore, the optimum curing time of this additive can be defined as 28 days. Although it seems that 10 gives the highest strength value in terms of mixture ratios, it should be considered that 15% and 20% also give similar results.

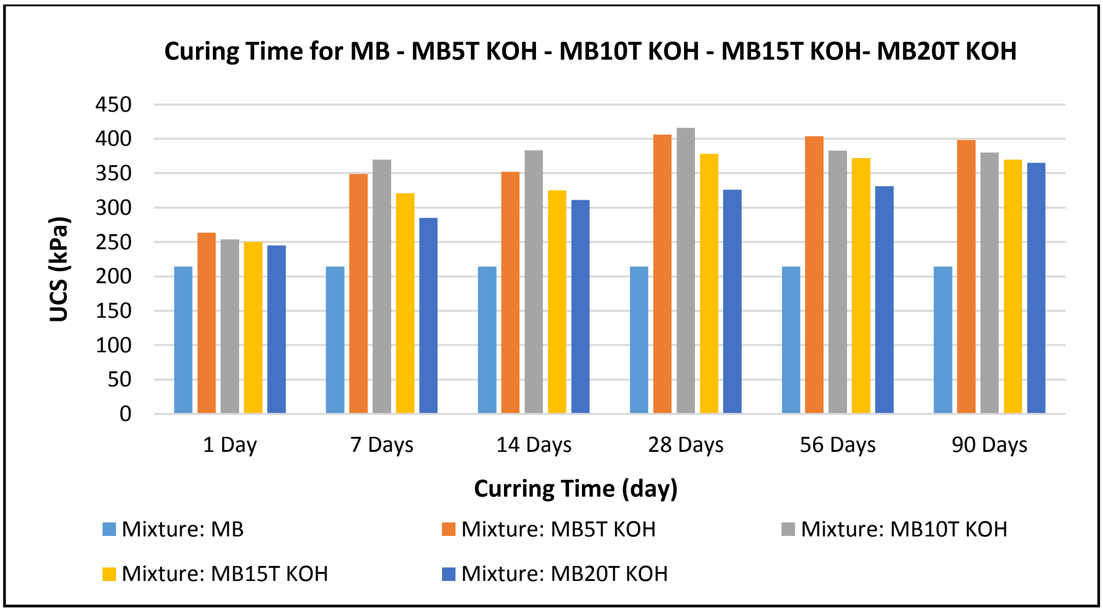


Figure 0.7. Curing Time for MB - MB5T KOH - MB10T KOH - MB15T KOH - MB20T KOH

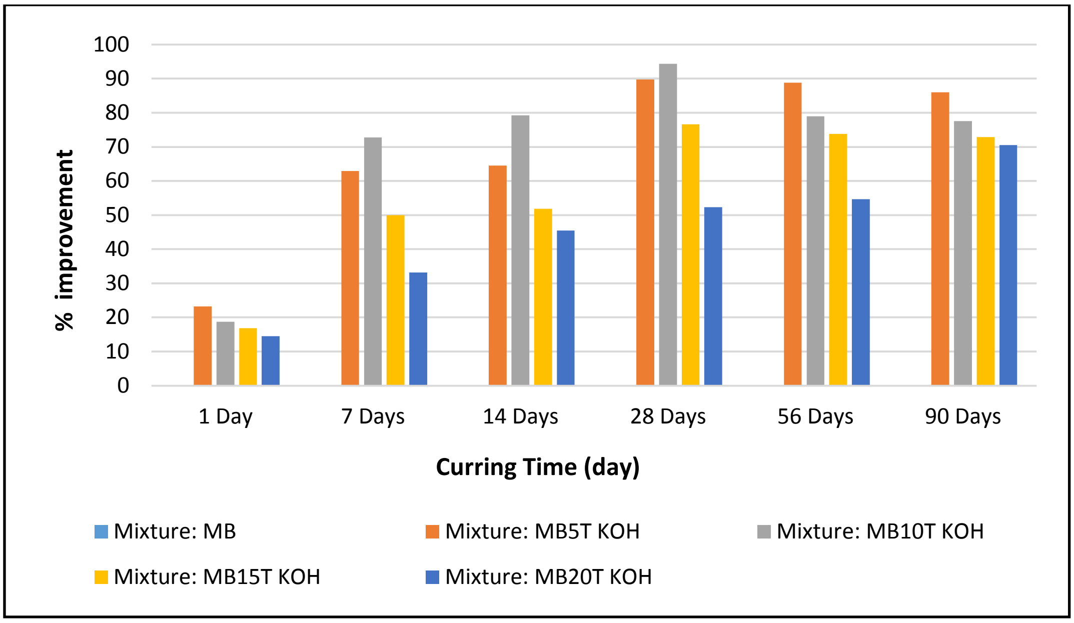


Figure 0.8. Curing Time for MB - MB5T - MB10T - MB15T - MB20T with KOH

All of the treated samples had a strength exceeding 345 kPa after the 28th day. This is the minimum strength level required to evaluate the potential use of new materials in soil stabilization as prescribed by ASTM D 4609 after 28 days of curing. These results prove the effectiveness of T activated by 1 mol KOH in rapidly increasing the mechanical strength of marl soil. The increase in soil strength properties over time following stabilization with T-KOH can be attributed to continuous hydration reactions resulting in the formation of additional hydration products. Stress versus strain curves for all MB - MB5T - MB10T - MB15T - MB20T samples with T- KOH at 1 - 7 - 28 – 56 and 90-day curing time are shown in Figure 4.9. In general, it is possible to say that more strain softening is observed in stabilized samples, and therefore, there is more ductile behavior for stabilized samples.

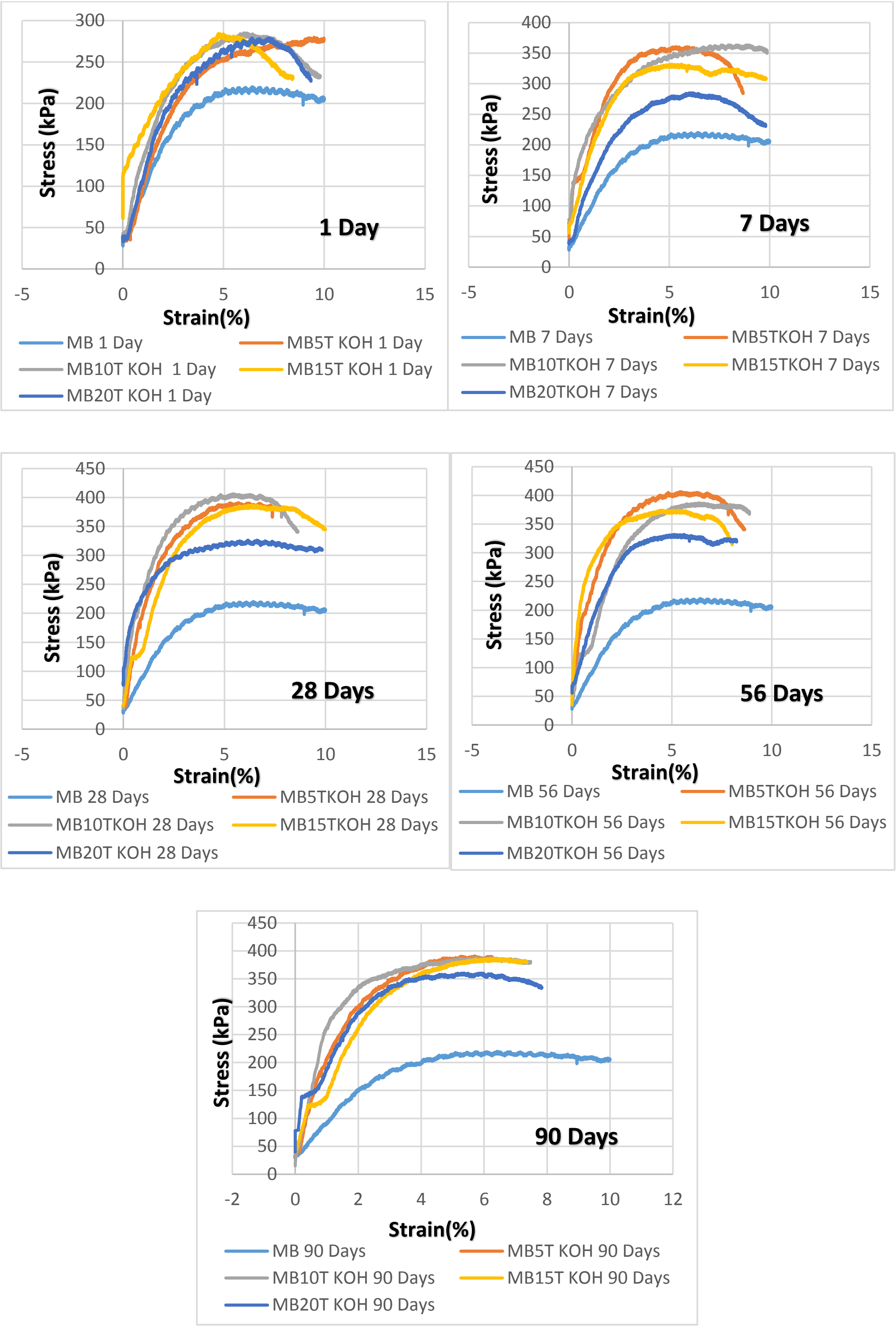


Figure 0.9. Unconfined Compressive tests of samples with KOH at 1 – 7 – 28 -56 and 90 days curing time

The results of comparison of MB5T - MB10T - MB15T - MB20T samples using KOH and without KOH are shown in Figure 4.10. As can be seen from the Figure 4.10, activation of travertine with KOH caused an increase in soil strength. The results from samples mixed with KOH revealed that the optimal values were attained with 15% travertine content after 90 days of curing. In contrast, samples without KOH displayed optimal values with 20% travertine content within a shorter curing period of 28 days.

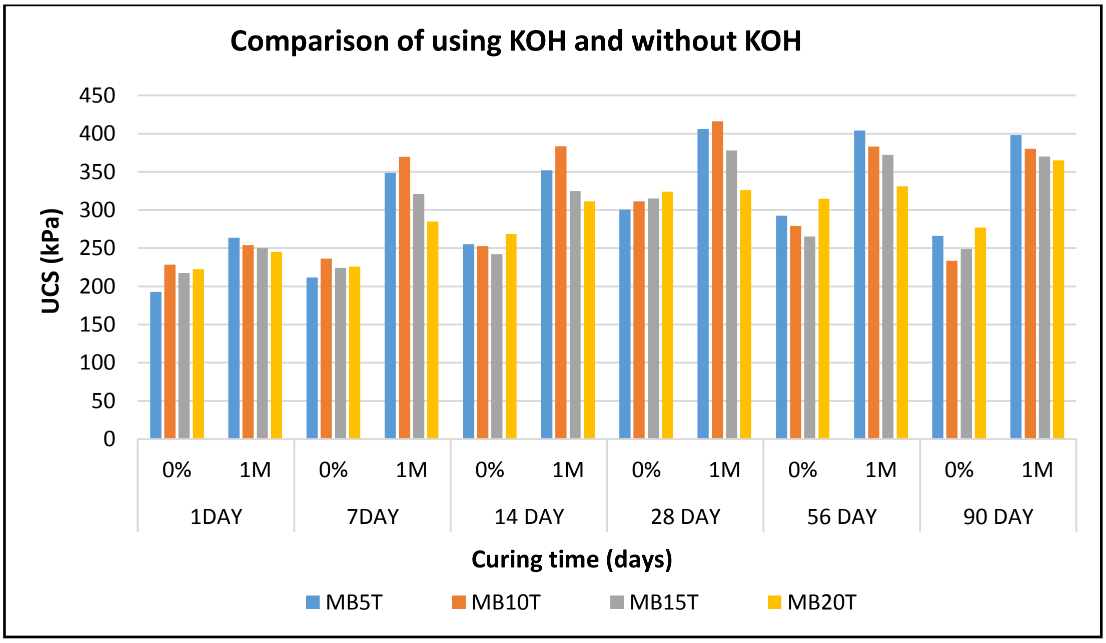


Figure 0.10. Comparison of using KOH and without KOH

4.5. FREE SWELLING PRESSURE TEST

In order to determine the effect of each additive material on the swelling pressure of the soil during curing, swelling pressures were determined with an experimental setup based on the constant volume method. In this context, samples prepared with optimum water content were used in the experiments. The free swelling pressure test was conducted based on ASTM for pure soil and all additives. The test measures how much a soil sample expands when it absorbs water, providing insight into its swelling potential. The Figure 4.11. presents a comprehensive depiction of the swelling behavior of different mixtures over time. The blue line represents mixture

MB, while the orange, grey, yellow, and light blue lines represent mixtures MB5T, MB10T, MB15T, and MB20T, respectively. These lines chart the swelling pressure exhibited by each mixture as time progresses from 0 to 10,080 minutes. According to the Figure 4.11, it becomes evident that all mixtures display an upward trend in swelling pressure over time. This indicates that as time elapses, the swelling behavior of each mixture intensifies. The gradual increase in swelling pressure suggests a progressive expansion or swelling of the mixtures. Notably, mixture MB, represented by the blue line, exhibits the highest swelling pressure among all the mixtures throughout the duration of the observation period. This observation suggests that mixture MB may possess unique properties or characteristics that contribute to its pronounced swelling behavior compared to the other mixtures studied. As can be seen from the Figure 4.11, 20% T contribution significantly reduced the soil swelling pressure.

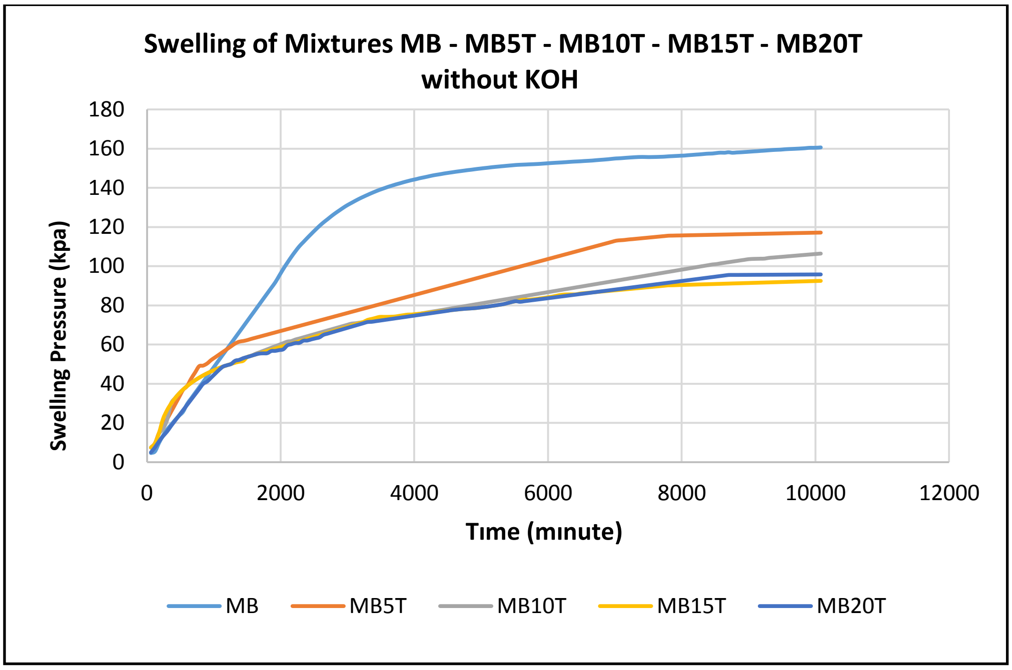


Figure 0.11. Swelling pressure of mixtures MB, MB5T, MB10T, MB15T, MB20T

Figure 4.12 provides a comprehensive visualization of the ground swelling behavior of different mixtures of KOH-activated T over time. First, all mixtures consistently tend to increase swelling pressure as time progresses. This observation indicates a gradual increase in the swelling behavior of each mixture over the study period. However, with the additive, the final swelling pressures of the soils decreased dramatically. The light blue line representing the MB mixture, a highly swellable soil, shows a significant increase in swelling pressure over the study period. However, with the addition of travertine activated with 1 mol KOH, the swelling pressure of the mixture decreased significantly. When the Figure 4.12 is examined, it is seen that the travertine concentration in the mixture affects the swelling behavior, and especially the 15%T-KOH mixture is the optimum value for the swelling pressure in the ground. This observation suggests that there may be a threshold concentration of travertine beyond which other mixing ratios will not significantly increase the swelling behavior of the soil.

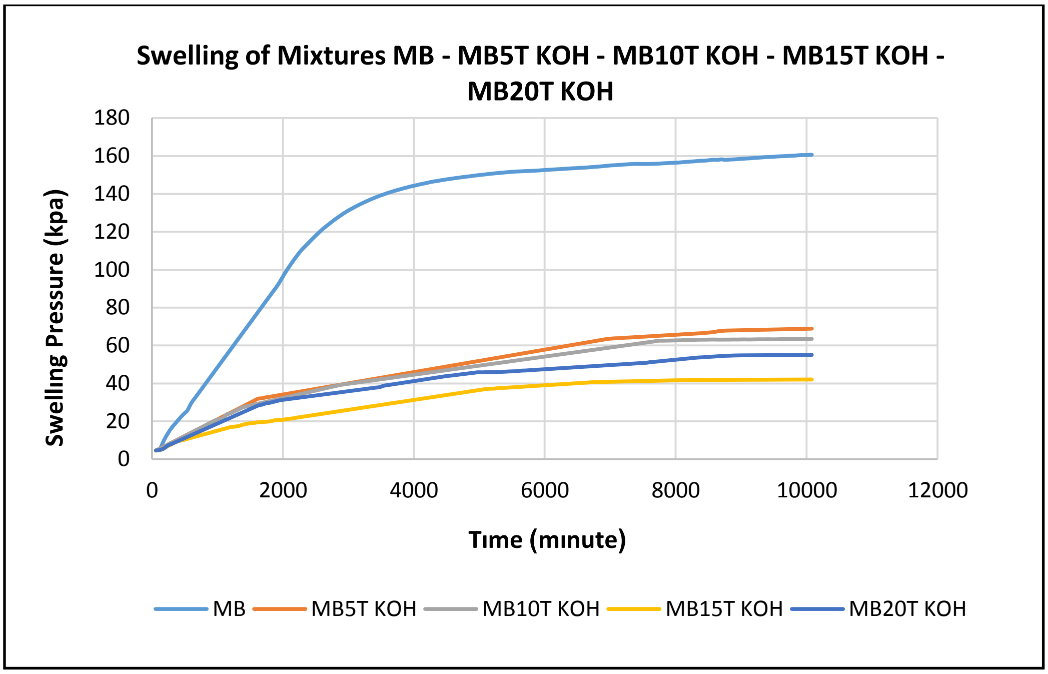


Figure 0.12. Swelling of Mixtures MB, MB5T-KOH, MB10T-KOH, MB15T-KOH, MB20T-KOH

Based on the obtained results across all percentages of travertine, it was determined that the optimal ratio is 15%. Subsequently, the free swelling test was conducted again using this optimal ratio for a duration of 1 day, and at intervals of 1, 2, and 3 weeks. The results for these tests are illustrated in Figure 4.13. The swelling behavior of two soil mixtures, MB (highly swelling) and MB15T, was studied over various time intervals. Initially, MB shows a sharp increase in swelling pressure within the first day, indicating rapid expansion likely due to high reactivity or moisture absorption. In contrast, MB15T demonstrates a slower increase in swelling pressure after 1 day, suggesting a potentially slower swelling rate over the observation period (1 Day - 1 Week - 2 Weeks - 3 Weeks. It was observed that the interval time had no significant effect on the swelling behavior of MB15T, as it consistently showed the same results across different time intervals.

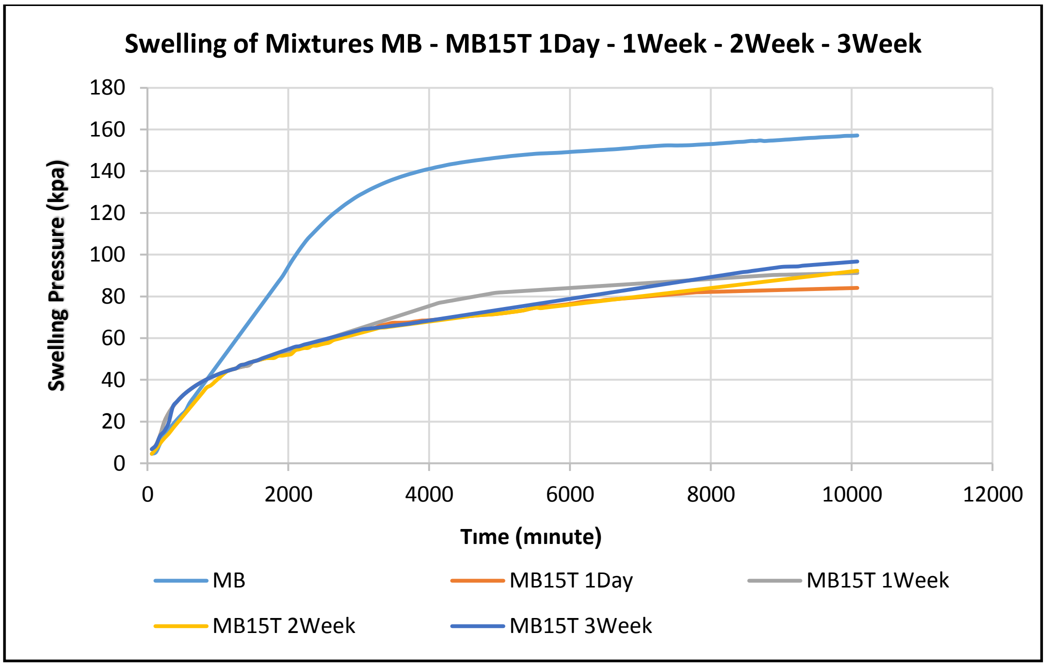


Figure 0.13. Swelling of Mixtures MB & MB15T 1Day - 1Week - 2Week - 3Week

4.6. LARGE SWELLING DEVICE

Using the interpretations of all data obtained, the effect of Travertine activated with KOH on the swelling behavior of clayey soils for shallow and deep soil improvement application was evaluated with the large-sized swelling pressure test device developed within the scope of this thesis study. The optimum ratio obtained from the small-scale free swelling method, details of which were given in the previous section, was used in the large swelling device (Figure 4.14). This developed device is designed to accommodate large-scale samples and precisely measure swelling properties over long periods of time. The device is also designed with two sensors (LVDT) to measure the swelling percentage of the soil inside the device. The sensors are connected to a data logger to record readings every second into an Excel file. In this context, firstly, the effect of applying the KOH-activated Travertine additive with the superficial stabilization technique in different thicknesses was evaluated. Then, the effect of the deep improvement method in the form of columns of different diameters was evaluated.

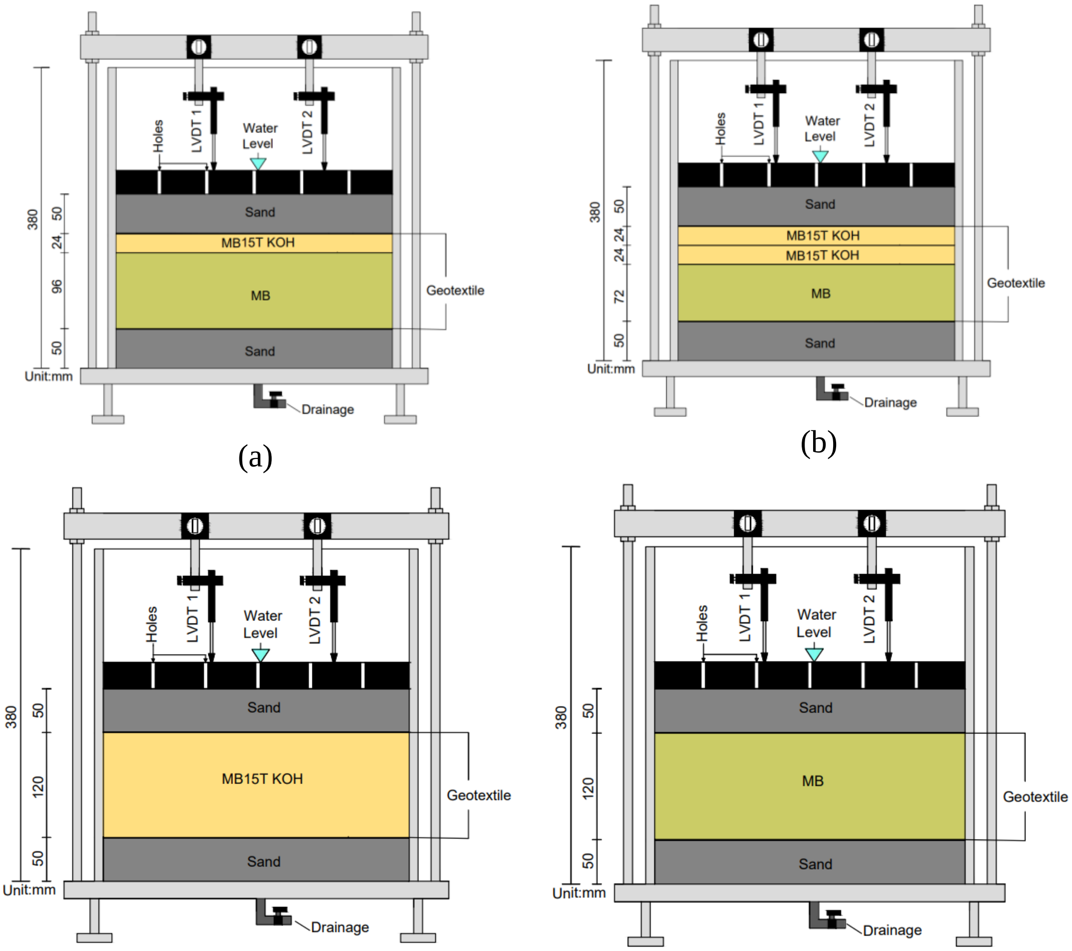
Figure 0.14. Device prepared for swelling measurement.

4.6.1. Shallow Stabilization

The study delved into the influence of thickness variations in shallow stabilized expansive clay on the swelling characteristics of composite clays. The thickness ratio (Tr), which is defined as the ratio of the stabilized thickness ($T(_{stabilized})$) to the initial thickness of the untreated expansive clay ($T(_{unstabilized})$), as per equation 4.1. Three layers were used 0 mm ($T_{unstabilized}$) (which represent marl and bentonint only without travertine), and 24 mm, 48 mm, and 120 mm ($T_{stabilized}$) (included travertine) where (T_r) equal to 0, 0.2, 0.4 and 1.0 respectivly. A compacted sand layer, 50 mm thick, was placed on both the top and bottom, separated by a geotextile sheet between the sand and clay layers. All prepared layers were statically compacted in accordance with (Tr) ratios using the optimum moisture content and maximum dry density.

$$T_r = T_{stablized} / T_{unstabilized} \qquad (4.1)$$

In the initial stage, with Tr equal to 0.2, the layers were compacted separately into 5 layers, each with a thickness of 24 mm. %15T-KOH was added solely to the topmost 24 mm layer, with a concentration of 1 molar maintained across all stabilized layers (Figure 4.15 a). In the second stage, with Tr equal to 0.4, the layers were also compacted separately into 5 layers, each with a thickness of 2.4 mm. %15T-KOH was added solely to the topmost and the second 48 mm layer, with a concentration of 1 molar maintained across all stabilized layers (Figure 4.15b). In the third stage, with Tr equal to 1.0, the layers were also compacted separately into 5 layers, each with a thickness of 2.4 mm. %15T-KOH with 1 molar was added solely to the all-clay layers with 120 mm (Figure 4.15 c). In the last stage, with Tr equal to 0, the layers were also compacted separately into 5 layers, each with a thickness of 2.4 mm without %15T-KOH, all clay layers with 120 mm thickness (Figure 4.15d).



(a) (b)

(c) (d)

Figure 0.15. Schematic diagram of composite free swelling tests of MB and MB15T-KOH for shallow application.

The effects of different shallow improvement applications used in the experiment on ground swelling are shown collectively in Figure 4.16. The blue line, representing the case when the experimental model was completely filled with MB, shows an initial rapid increase in swelling and then stabilized around 28 mm. The red line showing the result when MB15T-KOH is applied in 1 layer shows a similar trend but a less steep rise, settling at approximately 24mm. The gray line representing the data, when MB15T-KOH is applied in 2 layers of KMB15T-KOH, reaches slightly above 22mm, keeping the post-initial swelling relatively constant. The yellow line representing the data from filling the test device with MB15T-KOH shows that the swelling is limited to 17 mm.

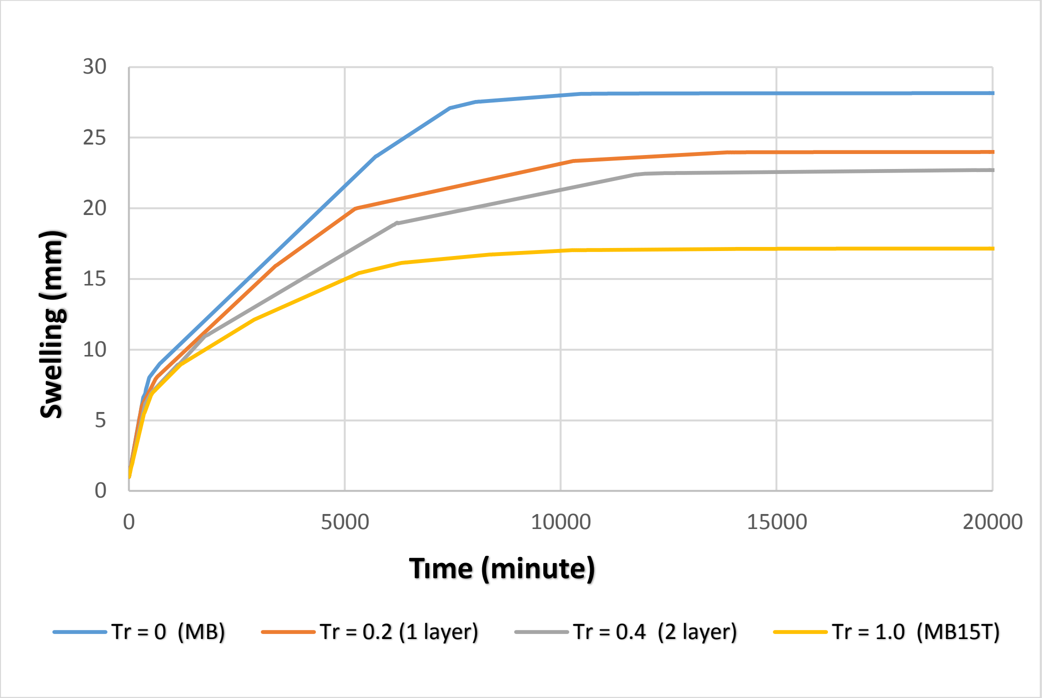


Figure 0.16. Swelling of Mixtures Full MB & MB15T KOH 1Layer - MB15T KOH 2Layer - Full MB15T KOH

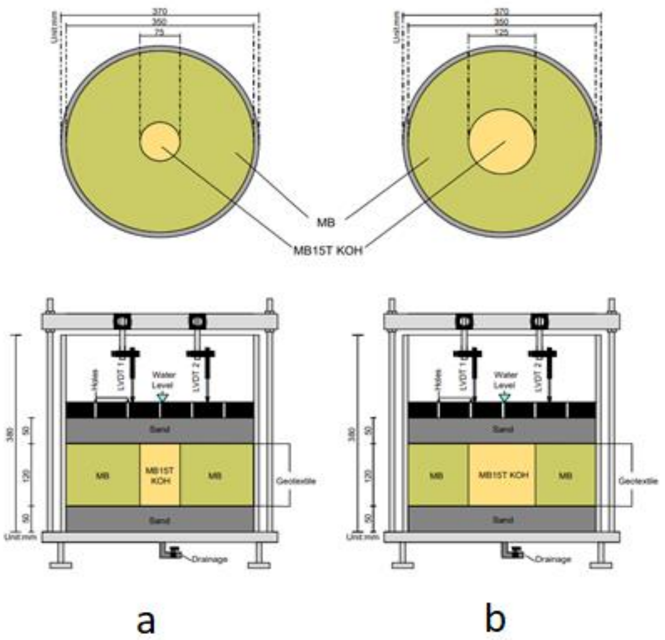
4.6.2. Deep Stabilization

The influence of diameter variations in deep stabilized expansive clay on the swelling characteristics of composite clays. This investaigation involved adjusting the improvement diameter ratio (Dr), which is defined as the ratio of the stabilized deep layer ($D_{(stabilized)}$) to the initial diameter of the untreated expansive clay ($D_{(unstabilized)}$), as per Equation 4.2. Four different diameters were used for ($D_{(stabilized)}$) deep thinkness with 0 mm ($D_{(unstabilized)}$), 75 mm, 125 mm, 160 mm, 200, and 350 mm of ($D_{(stabilized)}$) respectivly. Where (D_r) equal to 0, 0.21, 0.35, 0.45, 0.57 and 1.0 respectivly. Compacted sand layer with 50 mm was placed on the top and bottom separated with a geotextile sheet between sand and clay layers. All prepared layers were statically compacted in accordance with (D_r) rations using the optimum moisture conent and maximum dry density.

$$D_r = D_{(stabilized)} / D_{(unstabilized)} \qquad (4.2)$$

In the initial stage, with Dr equal to 0.21 and 0.35, the layers were compacted separately into 5 layers, each with a thickness of 24 mm. MB15T-KOH was added only to the inner diameter of 75 mm and 125 mm, with a concentration of 1 molar maintained across all stabilized layers (Figure 4.16a and 4.16b). In the second stage, with Dr equal to 0.45 and 0.57, the layers were compacted separately into 5 layers, each with a thickness of 24 mm. MB15T-KOH was added only to the inner diameter of 160 mm and 200 mm, with a concentration of 1 molar maintained across all stabilized layers (Figure 4.16c and 4.16d).

Based on Figure 4.18, it's clear that there's significant variation in the swelling behavior among the examined mixtures. The MB15T-KOH D75 mm mixture exhibits the highest swelling, while the MB15T-KOH with D200 mm shows the lowest swelling pressure.



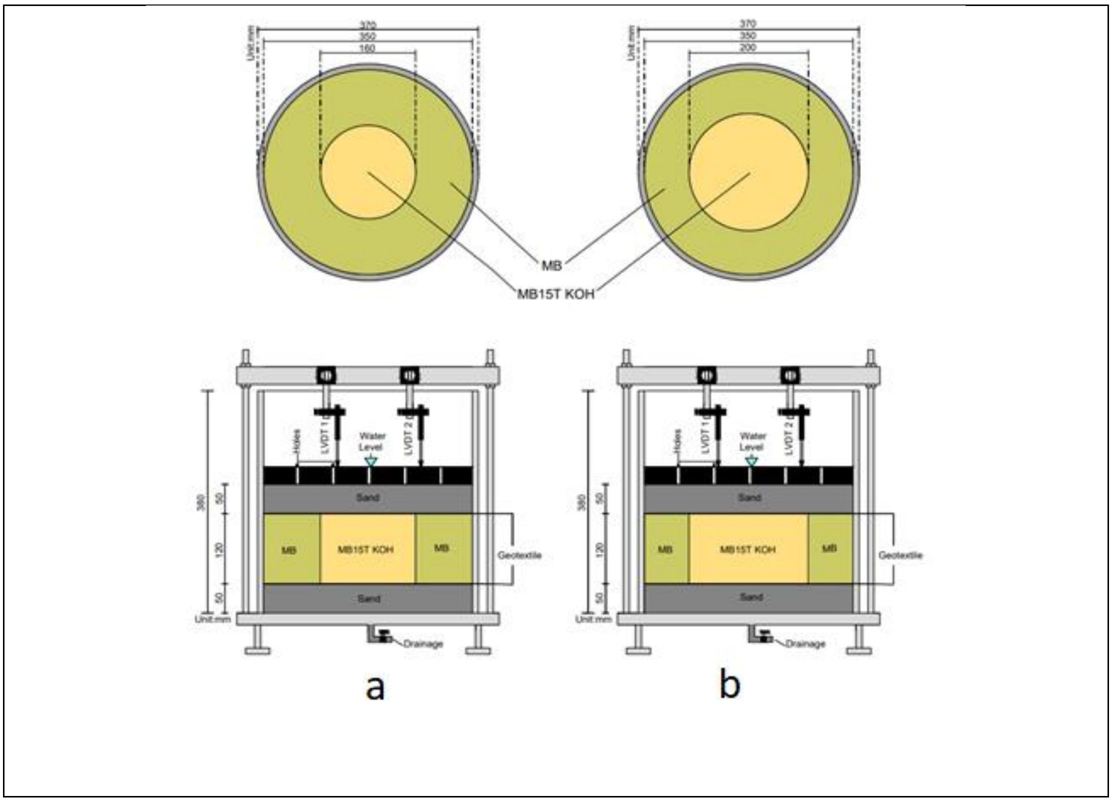


Figure 0.17. Schematic diagram of free swelling tests for deep column application

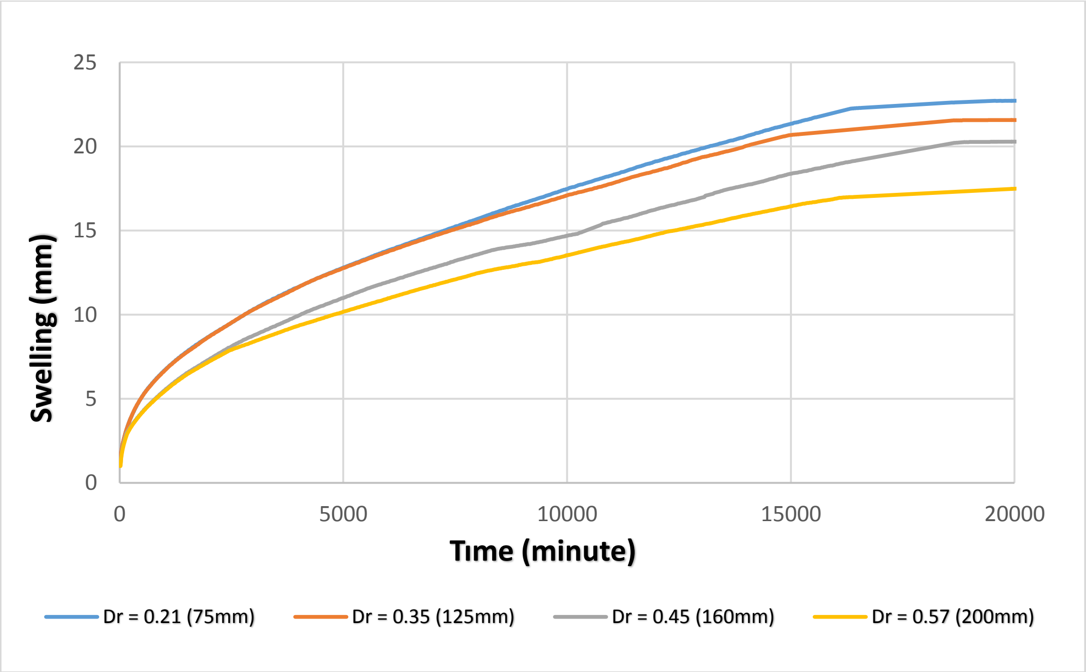


Figure 0.18. Swelling of Mixtures MB15T KOH D75mm - MB15T KOH D125mm - MB15T KOH D160mm - MB15T KOH D200mm

Offering insights into the swelling behavior of different mixes, Figure 4.19 shows the swelling load dynamics of those mixtures over a specified length of time. On Figure 4.19, each unique blend is indicated by a coloured line, facilitating comparison analysis. The MB15T KOH D75 mm Load is represented, which starts at zero and increases sharply until levelling out at about 23 mm in the 25,000 min. In the same way, representing the MB15T KOH D125 mm Load starts at zero and rises more gradually before levelling out at 21 mm in 20,000 min. Similar to this, representing the MB15T KOH D160 mm Load has a plateau that is just 20 mm at 10,000 min. On the other hand, that represents the Full MB15T KOH Load starts at zero, rises sharply, then quickly stabilizes at less than17 mm at 10,000 min. The whole MB15T KOH D200 mm that starts at zero, rises sharply, and quickly stabilises at 17 mm in 20,000 min, the Full MB quickly stabilizes at 28 mm in 30,000 min.

These data show that there are considerable differences in the swelling behaviour of the combinations under study. Out of all the compositions under investigation, the Full MB Load combination with the light blue line shows the largest swelling load. It is followed in order by MB15T KOH D75 mm Load, MB15T KOH D125 mm Load, MB15T KOH D160 mm Load, and MB15T KOH D200 mm Load. The MB15T KOH D200mm Load ratio is the finest. However, the lowest swelling ratio is achieved with the full MB15T load

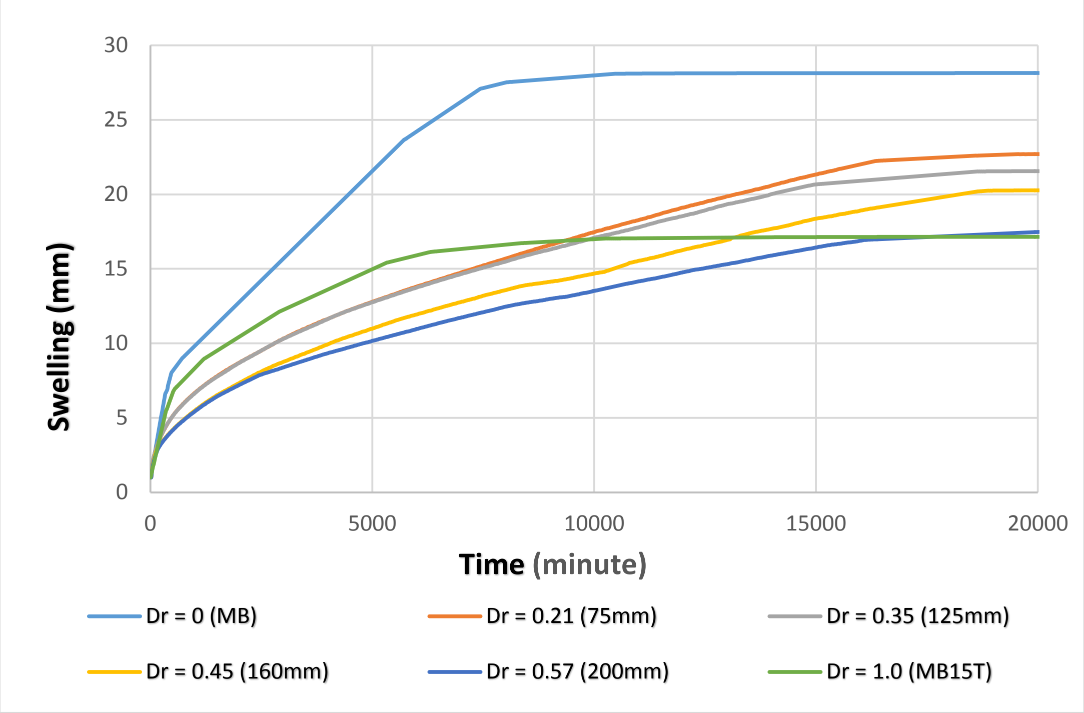


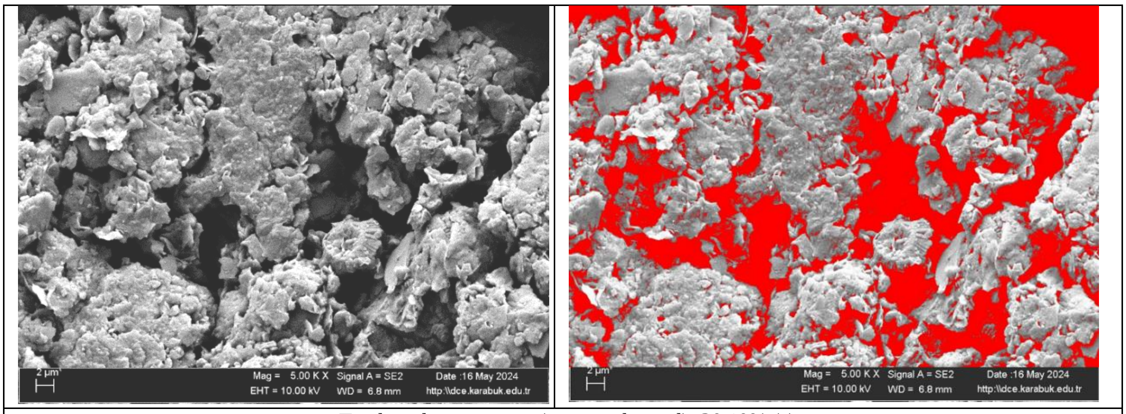
Figure 0.19. Swelling of Mixtures Full MB & MB15T KOH D75mm - MB15T KOH D125mm - MB15T KOH D160mm - MB15T KOH D200mm & Full MB15T KOH

4.6.3. Microstructural Properties of Mixed Soil

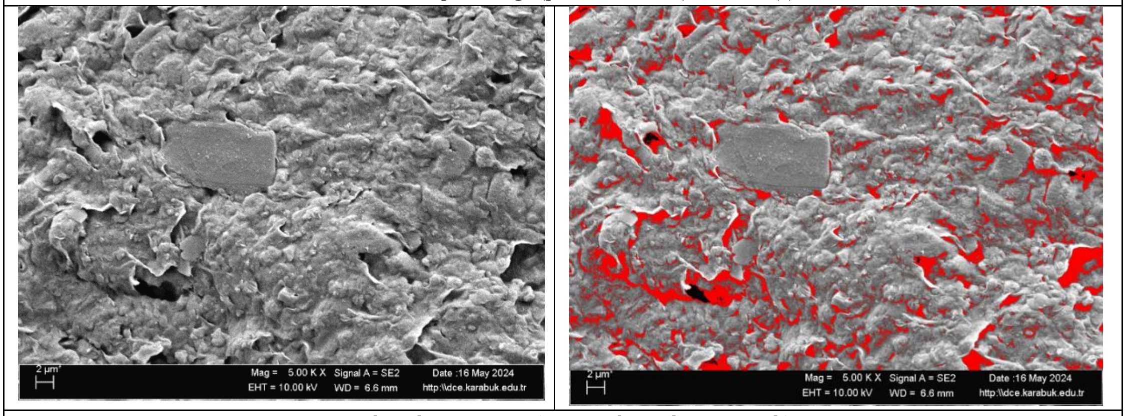
In this study, scanning electron microscopy (SEM), X-Ray Diffractometer (XRD) and X-ray fluorescence (XRF) was used before and after improvement to understand the physical and mechanical effects of additives on the soil at the micro level. The behavior of clays cannot always be interpreted according to their physical and mechanical properties. The microstructure of clay is very important in understanding soil behavior and the effects of additives. SEM provides magnified images of a sample's shape and size, composition, crystallography, and other physical and chemical properties. In this context, SEM can provide very valuable information, especially among microstructural analyses. Because the soil microstructure formed by clay particles and additives can be observed very easily with SEM [51]. In this study, it was thought that by examining the microstructural properties of improved clay with SEM analysis, the effect of clay particles and additives on the microstructure on the physical or mechanical behavior of the soil could be explained.

The microstructural analysis of the untreated and T and T-KOH-treated samples was conducted through SEM testing and SEMedx as depicted in Figure 4.23. The untreated BM sample exhibited a highly porous and soft structure with a significant volume of voids (i.e., 30.10% for 5.0 kX magnification magnification as shown in red). Therefore, the low strength of the untreated marl samples can be attributed to the weak particle connections arising from the presence of micro-voids within the soil particles and the discontinuous structure [52]

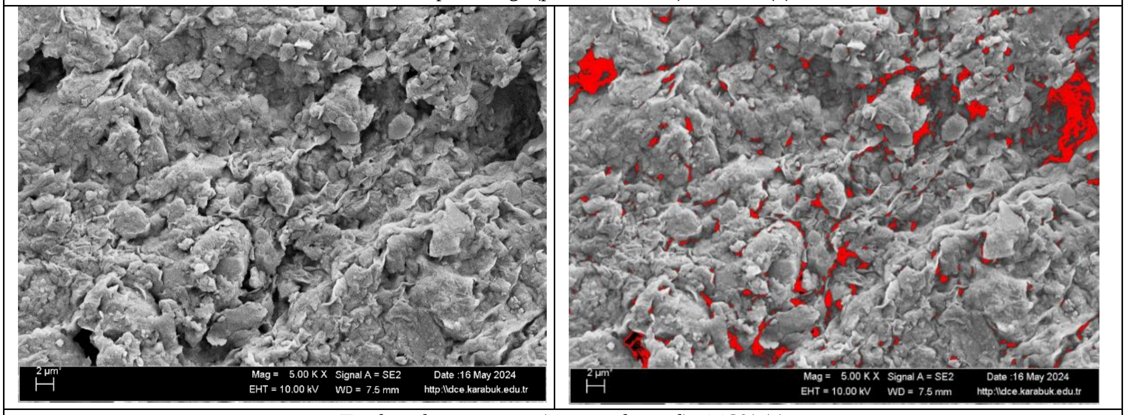
During stabilization with additives, cation exchange and flocculation - agglomeration occur in clayey soils. Calcium silicate gels are formed as a result of various reactions between clay minerals and additives. These gels fill the pores and act as a binder between soil particles, thus increasing the strength of the soil [51]. An agglomerated structure was identified in the cured-treated marl sample due to the binding of soil particles with compounds generated by the T and KOH activators. Additionally, a stronger link between soil particles created denser structures because this materials not only produces new chemical compounds but also effectively acts as a filling material for the voids in the soil [53] Hence, through the process of filling the gaps among the untreated soil particles, the size of voids is considerably diminished, resulting in a more stable and compact structure (i.e., 10.19% for 5.0 kX magnification and 4.231% for 5.0 kX magnification as shown in red). In summary, the incorporation of T and especially KOH into soil effectively increases active ions concentration and system alkalinity, thereby promoting crucial reactions such as pozzolanic and carbonization reactions that contribute to enhancing the mechanical properties of marl samples by generating additional hydration products [54–56]. In conjunction with the pozzolanic reaction, the inclusion of T with KOH can lead to the formation of flocs through polymerization and flocculation reactions, resulting in soil strengthening [57].



Total voids percentage (presented in red): 30.10% (a)



Total voids percentage (presented in red): 10.19% (b)



Total voids percentage (presented in red): 4.23% (c)

Figure 0.20. SEM micrographs: (a) BM, (b) T-BM stabilized marl soil, (b) and (c) T-KOH-BM stabilized marl soil.

Travertine consists mainly of calcium carbonate ($CaCO_3$). XRD analyzes have shown that gels such as CSH, CAH do not form when Travertine reacts with clay (Figure 4.24). CSH formation generally results from the reaction of portlandite ($Ca(OH)_2$) and silica (SiO_2) components. It was concluded that these reactions did not occur during curing and the improvement in the soil was explained by physical change.

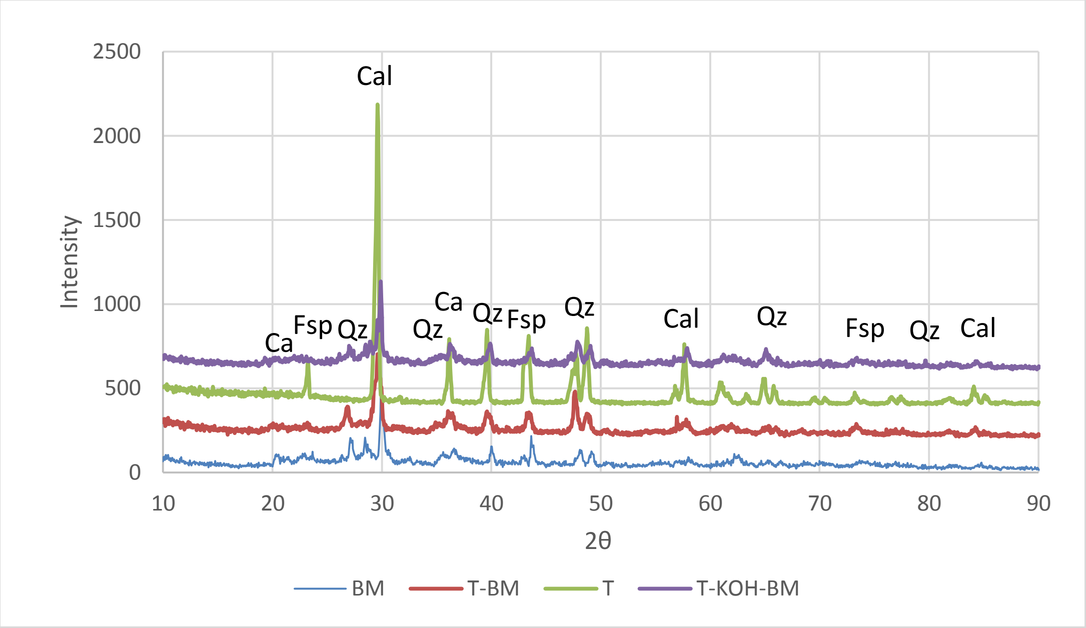


Figure 0.21. XRD pattern of stabilized marl soil, Traverten, and marl soil.

CONCLUSION

The culmination of extensive experimentation and analysis in this study offers valuable insights into understanding and mitigating soil swelling, particularly through the stabilization effects of travertine. With a focus on clay mixtures stabilized with travertine, the research delved into various aspects ranging from compaction properties to long-term swelling behavior and mechanical properties. Through a systematic approach and rigorous testing regime, the study provides significant contributions to the fields of geotechnical engineering, construction practices, and environmental management.

One of the key findings of the study revolves around the significant role of travertine in reducing soil swelling. By adding varying percentages of travertine to the clay mixtures, it was observed that travertine contributes substantially to mitigating soil swelling, particularly when combined with an activator such as potassium hydroxide (KOH). The optimal proportion of travertine, determined to be around 15%, demonstrated notable effectiveness in reducing soil swelling, highlighting its potential as a viable stabilization agent in soil engineering projects.

Furthermore, the study sheds light on the interaction between travertine, moisture levels, and other soil constituents such as bentonite and marl. Through meticulous laboratory testing, including compaction tests and liquid limit-plastic limit tests, the research elucidated the complex behavior of clay mixtures under different moisture conditions and provided valuable insights into their plasticity and consistency. Understanding these fundamental properties is crucial for engineering design and construction practices, as it enables informed decision-making and effective soil stabilization strategies.

The utilization of both small-scale and large-scale swelling devices played a pivotal role in elucidating the short-term and long-term swelling behavior of the soil mixtures. By subjecting samples to controlled swelling conditions, the study provided comprehensive data on soil expansion reduction effects over time. Concurrent compressive strength evaluations, conducted at various curing times, further enriched the understanding of the connection between swelling behavior and mechanical properties. These findings underscore the intricate interplay between soil composition, swelling dynamics, and mechanical performance, offering valuable guidance for engineering design and construction processes.

Moreover, the comparative analysis between shallow and deep mixing methods provided valuable insights into soil stabilization techniques. By introducing a mid-layer modification with 15% travertine in the bentonite-marl mixture, the study aimed to evaluate the efficacy of shallow mixing in reducing soil swelling. The results indicate promising outcomes, suggesting that shallow mixing techniques, coupled with travertine stabilization, can effectively enhance soil stability and mitigate swelling potential. This underscores the importance of exploring innovative stabilization methods for sustainable soil management practices.

The recommendations derived from the study offer practical guidance for future research and engineering applications. The suggestion to experiment with different proportions of travertine, particularly in combination with other soil stabilizers, opens avenues for further investigation and optimization of soil stabilization techniques. Additionally, the observed correlation between swelling behavior and curing time highlights the importance of considering long-term performance factors in soil engineering projects. By integrating these insights into engineering practices, stakeholders can enhance the resilience and sustainability of infrastructure projects while minimizing environmental impact.

This study provides a comprehensive understanding of the swelling behavior of clay mixtures stabilized with travertine and offers valuable insights into effective soil stabilization strategies. By elucidating the complex interplay between soil composition, moisture levels, and mechanical properties, the research contributes to advancing knowledge in geotechnical engineering and environmental management. The findings underscore the significance of informed decision-making and innovative approaches in addressing soil swelling challenges, ultimately paving the way for more sustainable and resilient infrastructure development.

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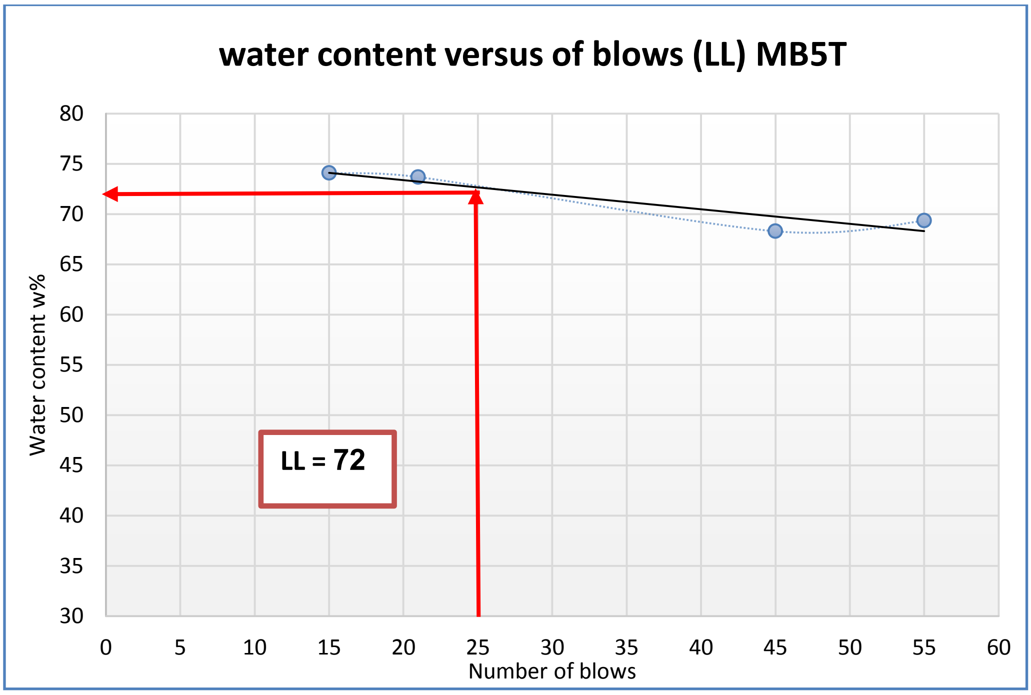
ADDITIONAL EXPLANATIONS A.

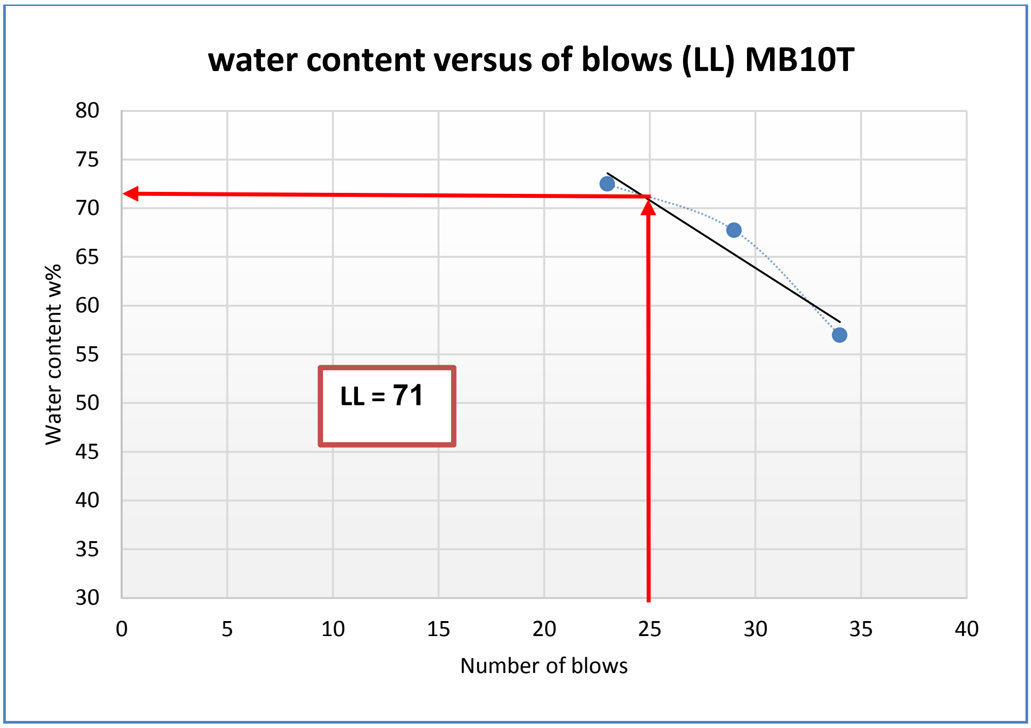
SAMPLE RESULTS

Appendix 1

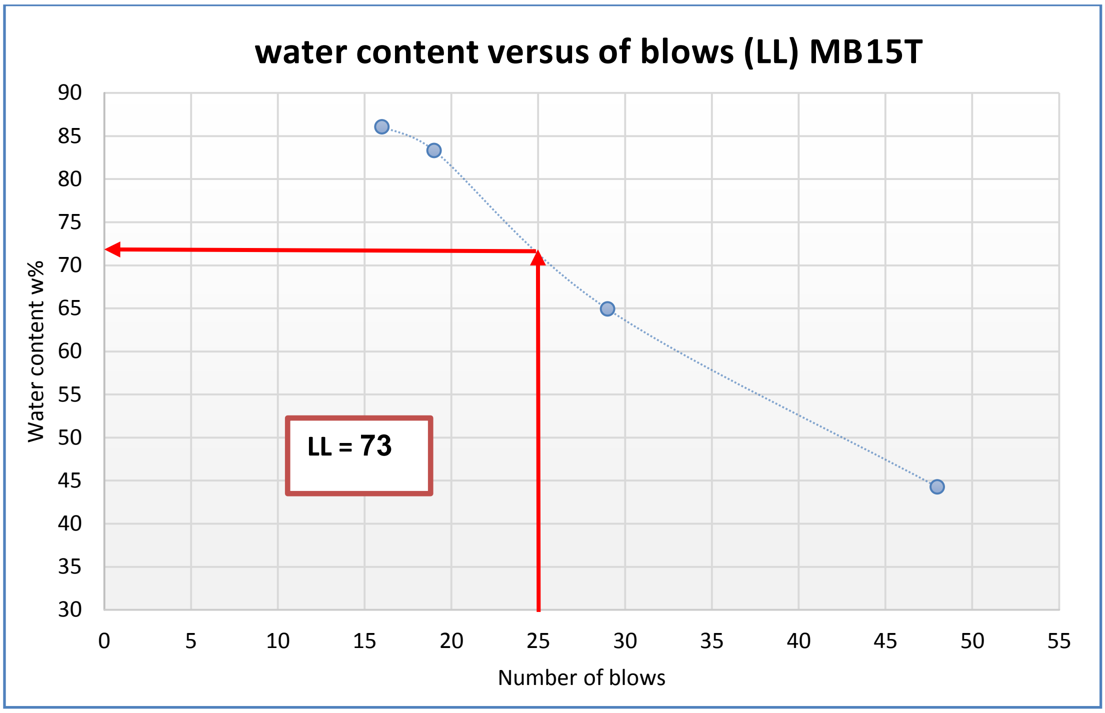
Liquid limit of MB5T



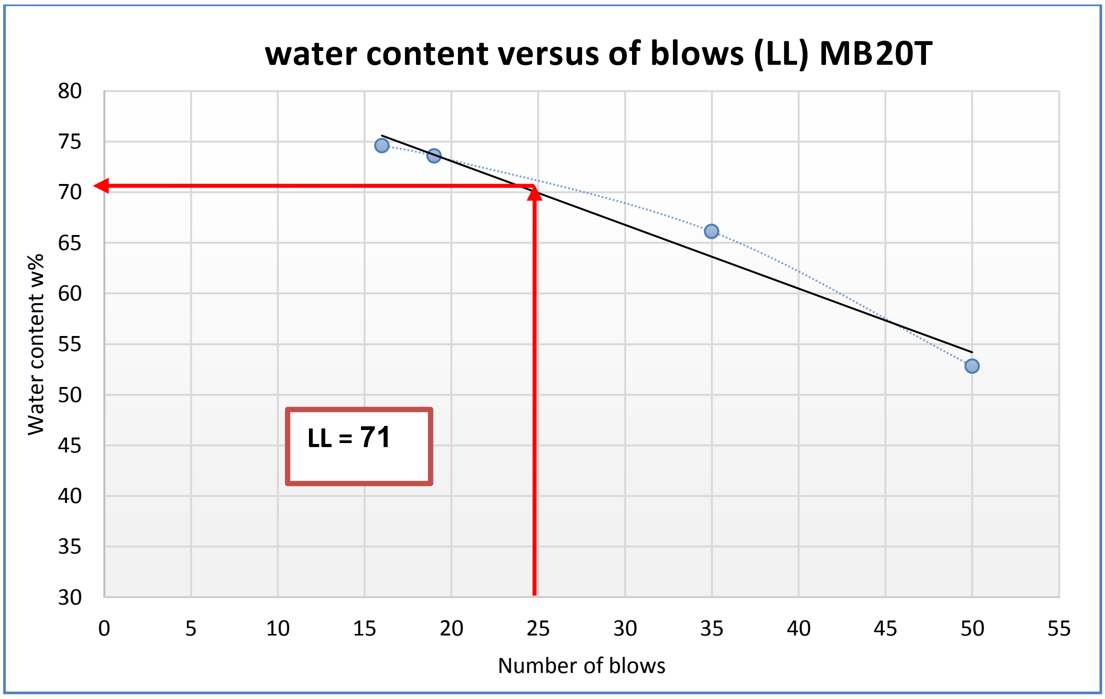
Liquid limit of MB10T



Liquid limit of MB15T



Liquid limit of MB20T



RESUME

I am Almukhtar Hasan Salih IQBAS I completed my secondary education at the Engineering High School, and then I started my bachelor’s degree program at Zawiya College of Building and Construction Engineering, Civil Engineering major. I graduated in 2010. After that, I worked with an engineering company to design and construct buildings. Then in 2022, I started my master’s degree at Karabuk University, Civil Engineering Department